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STUDY OF LASER BACKSCATTER BY PARTICULATES
IN STACK EMISSIONS

Edward E. Uthe, et al

Stanford Research Institute

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Final Report

**STUDY OF LASER BACKSCATTER BY
PARTICULATES IN STACK EMISSIONS**

By: EDWARD E. UTHE and CHARLES E. LAPPLE

Prepared for:

ENVIRONMENTAL PROTECTION AGENCY
NATIONAL ENVIRONMENTAL RESEARCH CENTER
DIVISION OF CHEMISTRY AND PHYSICS
RESEARCH TRIANGLE PARK
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ABSTRACT

This experimental study investigates the validity of determining smoke plume opacity or particulate content from measurements of the backscatter of laser radiation from plume particulates. The backscatter experiments were conducted with the use of a specially designed aerosol chamber that allowed the experimental geometry to simulate that associated with actual remote plume probing.

The backscatter experiments used fly ash collected from a bituminous coal-burning power plant. The raw fly ash was classified into various size fractions and pneumatically injected into the chamber at controlled concentrations. The aerosol was continuously monitored by a white light transmissometer along the axis of the chamber. Lidar measurements were made to determine the backscatter and transmission of the generated aerosols.

At a wavelength of 0.7μ , the backscatter-to-extinction ratio was essentially independent of particle size, and the backscatter-to-mass concentration ratio was inversely proportional to the volume-to-surface mean diameter. At a wavelength of 1.06μ , the backscatter-to-extinction ratio was more dependent on particle size and the backscatter-to-mass concentration ratio was less dependent on particle size than at the 0.7μ wavelength. Transmission data at both lidar wavelengths agreed with the white light transmission data. Mie theory computations of backscatter and extinction values agreed reasonably well with observed data.

These results for fly ash indicate that plume opacity may be determined from lidar backscatter measurements at 0.7μ wavelength, but that mass concentration is better inferred from 1.06μ lidar backscatter measurements. At either wavelength, lidar measurements of transmission may be used to determine plume opacity.

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I INTRODUCTION

Enforcement of increasingly stringent air pollution laws governing emissions from pollution sources requires the development of objective direct- and remote-sensing techniques. One major problem is the remote evaluation of aerosol density emitted from stationary sources in terms of legally acceptable parameters. Subjective plume opacity reading by a human observer (the Ringelmann procedure) is the method used by most pollution control agencies. The present study is concerned with certain aspects of the development of an instrument for the objective measurement of plume opacity or density.

Remote measurement of stack effluent opacity using a pulsed laser technique has been described and demonstrated by Evans (1967), Conner and Hodkinson (1967), and Cook et al. (1971). Single-ended measurements of laser energy transmission through stack plumes are made by comparing "clear air" backscatter returns from the near and far side of the plume return. However, to obtain the necessary signal levels, a relatively expensive pulsed lidar with high transmitter energy and a highly sensitive low noise receiver is required. In addition as Evans reported, sensitive light-receiving photomultiplier tubes may become "saturated" from the plume return and may not recover sufficiently to make accurate measurements of the clear air backscatter from the far side of the plume.

An alternative approach, the remote inference of plume density by measurement of elastic backscatter of laser radiation from plume particulates, would place fewer requirements on the lidar components. However, the inference of plume particulate content from the laser radiation backscattered from these particulates is susceptible to errors originating

from inherent uncertainties of particle backscatter cross sections (Twomey and Howell, 1965).

The objective of this experimental study was to investigate laser backscatter from plume particulates in terms of plume opacity, transmission at laser wavelengths, and mass concentration. The collected data are presented and analyzed in terms of developing a low cost, plume-measuring instrument.

II SUMMARY AND CONCLUSIONS

The experimental facility and lidar techniques used during this study and the results obtained are described briefly below. Conclusions of significance to the development of a low cost plume-monitoring instrument are presented.

A. Experimental Facility and Procedures

A major effort of the present study was to design and assemble an experimental facility to be used for the evaluation of laser backscatter techniques from aerosols consisting of particulates of known characteristics and in known concentrations. The following experimental work was performed:

- (1) A special aerosol chamber was designed and constructed. The chamber dimensions (20 in. square and 30 ft long) are sufficient to enclose completely a Q-switched laser pulse and allow the pulse to propagate through the test aerosol without interaction with any chamber surfaces.
- (2) Raw fly ash was collected from a coal-burning power plant and was divided into various size fractions in the 0 to 10 μ diameter range. The classified fractions were analyzed by the Fisher Sub-Sieve Sizer, MSA-Whitby Sedimentation Analyzer, and Coulter Counter techniques to determine their particle size distribution.
- (3) A white-light transmissometer and a 90° side-scattering photometer were constructed and mounted in the aerosol chamber for continuous aerosol monitoring. The optical instrumentation was specially designed to reduce multiple scattering effects and not to interfere with propagation of the laser pulse through the test aerosol. (The 90° side-scatter photometer was not extensively used because of low-signal-to-noise problems during daylight conditions.)

- (4) The fly ash fractions were pneumatically injected into the chamber at various concentrations by a rotating-disk particle feeder. The particle feeder was calibrated in terms of mass concentration for each fly ash fraction by separately measuring dust rates from the feeder at various feeder speeds.
- (5) Extensive particle-sampling was conducted at various locations within the chamber to assess the degree of uniformity of particulate concentration.
- (6) The white-light transmissometer data were calibrated in terms of particulate mass concentration for each fly ash fraction by relating time-averaged transmissions to the calibrated particle feed rates.
- (7) Lidar observations of the test aerosol were made 500 ft from the aerosol chamber. The lidar backscatter signatures were recorded on Polaroid film using several oscilloscope displays to provide a linear reading of return signals that can vary over several orders of magnitude. Concurrent lidar and chamber measurements of aerosol concentration were conducted as a function of particulate concentration, particulate size (using the various fly ash size fractions), and lidar wavelength (0.7 and 1.06 μ).

B. Data Analysis

Each lidar observation (firing) produced relative measurements of: transmitted peak power, peak power return (backscatter) from the test aerosol, and peak power return from a black passive reflector placed beyond the aerosol chamber. These recorded quantities were interpreted in terms of aerosol transmission at the lidar wavelength, relative backscatter from the test aerosol, and absolute backscatter (volume backscatter coefficient) by assuming values for the laser pulse length and the reflectivity of the passive reflector. Then these lidar-derived quantities were related to aerosol mass concentrations and white-light extinction coefficients derived at the chamber site for each fly ash fraction. All data are presented as mass concentrations or optical coefficients that are independent of experimental geometry.

C. Results and Conclusions

Data plots of lidar-derived aerosol backscatter showed a linear relationship with respect to aerosol mass concentration and volume extinction coefficient at low concentrations, becoming nonlinear at high concentrations. Although detector saturation or limited instrumentation bandpass could explain this result, it was concluded that within-pulse attenuation by the test aerosol caused the observed nonlinearity. A model expression that includes this nonlinear effect as a correction factor to the expected linear relationship was fitted to the observed data using a nonlinear least-squares procedure.

Data collected at a lidar wavelength of $0.7\ \mu$ showed that the relationship between backscatter and the volume extinction coefficient for white-light is nearly independent of the particle size distribution. Since extinction is related to the second moment of the particle size distribution this result indicates that backscatter is similarly related. Data collected at a lidar wavelength of $1.06\ \mu$ showed that backscatter is less related to extinction but more nearly related to the third moment of the size distribution than at a lidar wavelength of $0.7\ \mu$. This suggests that interpretation of lidar backscatter data in terms of plume opacity is best achieved at a lidar wavelength of $0.7\ \mu$ and that interpretation in terms of mass concentration is best achieved at a lidar wavelength of $1.06\ \mu$. The degree of experimental data scatter between aerosol backscatter and mass concentration was similar for low and high density plumes.

Extinction coefficients observed at the two lidar wavelengths agreed with those observed with white light from the transmissometer records. Hence, valid plume opacity measurements may be made by observing the near and far side clear air returns at either lidar wavelength. The extinction at the two wavelengths is sufficiently similar

to discourage any attempt to determine mass concentration by comparing observations of extinction at these two wavelengths. However, an improved inference of mass concentrations may be possible by comparing backscatter from the plume particulates at these two wavelengths.

Observed relationships among aerosol mass concentrations, volume extinction coefficients and volume backscatter coefficients were compared with those computed by use of the Mie scattering theory for spherical particles assuming the results of the particle size analysis. In general, the theoretical and experimental results agreed for each fly ash fraction. The close agreement between theory and experiment encourages confidence in the experimental techniques used, which can now be extended to study backscatter from particulates for which theory is not complete (such as backscatter from volumes of irregularly shaped particles).

In general, the main conclusion of the study is that the experimental techniques developed are valid and useful for evaluation of laser plume measurement instrumentation and for investigating the scattering properties of particulate volumes. In particular, the experiments show to a substantial extent (but not conclusively) for fly ash from coal-burning power plants that:

- (1) A lidar measurement of plume opacity by observing the clear air returns from the near and far side of the plume return is valid; i.e., plume transmission at lidar wavelengths of $0.7\ \mu$ and $1.06\ \mu$ and white light are equal within experimental error.
- (2) A lidar measurement of plume particulate backscatter at $0.7\ \mu$ wavelength may be interpreted in terms of opacity regardless of particle size distribution. The relationship between plume backscatter and opacity is not so well defined at $1.06\ \mu$ wavelength.
- (3) The relationship of backscatter to particulate mass concentration is less dependent on particle size at $1.06\ \mu$ than it is at $0.7\ \mu$.

- (4) The relationship between plume backscatter and plume opacity at 0.7μ wavelength is less dependent upon particle size than is the relationship between plume backscatter and particulate mass concentration at 1.06μ wavelength.
- (5) Comparative measurements of backscatter at both 0.7μ and 1.06μ wavelength are likely to give better indications of particulate concentration than are single wavelength measurements. Dual wavelength measurements of extinction, however, do not appear to offer a similar advantage, due to the relatively small dependence of extinction upon wavelength.

III DISCUSSION OF EXPERIMENTAL PROGRAM

A. Experimental Facility

An especially designed experimental facility was developed to study laser backscatter from a volume of particulates. The facility allowed the investigation to be conducted in a manner that nearly duplicates the geometry of actual remote plume evaluation. Figure 1 shows the experimental set up, including lidar, aerosol chamber, and particle feeder. The chamber dimensions (20 in. x 20 in. x 30 ft) are sufficient to enclose the effective scattering portion of a Q-switched laser pulse (typically 20 to 30 ns). Particle-laden air curtains at both ends of the chamber effectively isolate the test aerosol from the surrounding environment without affecting transmission of the laser pulse as it traverses a path through the chamber. Additional design details of the aerosol chamber are included in Appendix A.

B. Experimental Procedures

Particulates of known size distribution, shape, and refractive properties were pneumatically injected into the chamber at controlled concentrations by means of a rotating disk particle feeder (see Appendix A). The generated aerosol was continuously monitored by a white light transmissometer along the axis of the chamber and, during periods of low background light levels, by a photomultiplier viewing 90° sidescatter from a small portion of the transmissometer beam. (Further details of these optical components are included as Appendix D.)

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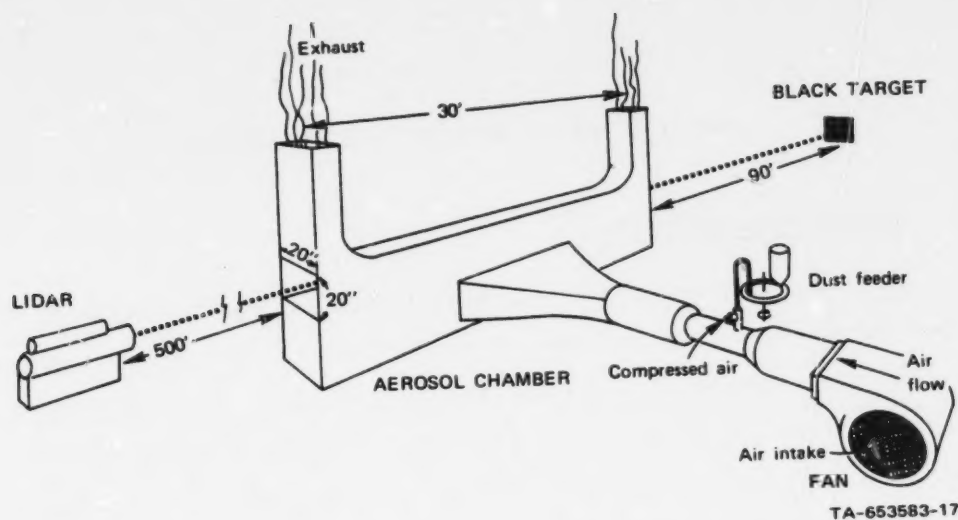


FIGURE 1 DIAGRAM OF EXPERIMENTAL SYSTEM

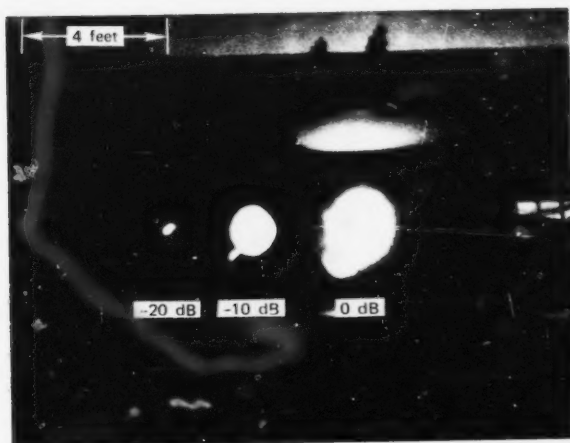
The lidar (laser radar) was placed 500 ft from the chamber. The lidar consists basically of a laser transmitter that emits a very brief, high intensity pulse of coherent light and a receiver that detects the energy at that wavelength backscattered from the atmospheric aerosol as a function of range. The resulting signal was displayed on an oscilloscope and photographed. The lidar data records consist of Polaroid prints that display relative transmitted peak power, peak power return from the aerosol within the chamber, and peak power reflected from a black passive reflector placed on the far side of the chamber. Further discussion of the lidar characteristics and data recording procedures are found in Appendix F.

Fly ash from a large coal-burning power plant was used for the particulate matter in the backscatter experiments. Raw fly ash was collected and classified into various size fractions and these were then subjected to various particle size analysis. Appendix B discusses the results of particle size classification and analysis. Basically, the fly ash used

in the backscatter experiments consisted of four size fractions (0-2.5, 2.5-5, 5-10, and 0-10 μ diameter).

Valid measurements of aerosol backscatter required that the laser pulse pass through the aerosol chamber with negligible energy incident on the chamber surfaces. Since light reflected from the chamber could not be distinguished from light backscattered from the chamber aerosol during an experimental run, extensive efforts were made to eliminate this problem area. The lidar van was isolated from its shock mountings so that lidar pointing was independent of weight loads or movement within the van. The receiver field of view was coaligned with transmitted laser pulses. The lidar was then aligned with the aerosol chamber. Initial lidar observations made with a clean air chamber showed laser returns from the chamber so that further modifications were necessary.

Infrared Polaroid photographs of the laser pulse size at the chamber location (Figure 2) showed that the laser energy could be detected over a diameter of 18 inches (21-inch skirt). Photographs made by inserting neutral density filters in front of the camera optics reduced the spot size to 16 inches for a 10-dB filter and to 4 inches for a 20-dB filter. An upper limit to the spot size at the energy halfpower points (3 dB) is estimated as 6 inches. However, the solid surfaces of the aerosol chamber caused significant energy return from the beam skirts (from energy at least 10 dB down from that at the beam center). It was desirable to reduce the beam size sufficiently so that negligible returns were received from the clean air chamber. This was accomplished by inserting an optical stop within the laser transmitter. Figures 2(b) and 2(c) illustrate the laser pulse size before and after inserting an optical stop. Negligible energy was intercepted and reflected back to the lidar by the chamber surfaces with the optical stop in place.



(a) PHOTOGRAPH OF LASER BEAM FOR VARIOUS DEGREES OF ATTENUATION BY NEUTRAL DENSITY FILTERS



(b) PHOTOGRAPH OF LASER BEAM FOR 10 LASER FIRINGS BEFORE PLACEMENT OF TRANSMITTER OPTICAL STOP
TAPE LENGTH EQUALS 4.3 inches

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best available copy.



(c) PHOTOGRAPH OF LASER BEAM FOR 10 LASER FIRINGS AFTER PLACEMENT OF TRANSMITTER OPTICAL STOP

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FIGURE 2 PHOTOGRAPHS OF LASER BEAM SIZE AT CHAMBER LOCATION

The photomultiplier tube was tested for its range of output linearity. At high light levels the tube became saturated and behaved in a nonlinear fashion. A neutral density filter was placed within the receiver optical path (see Appendix F) so that the return pulse from the passive reflector was within the linear operating region of the photomultiplier. Unfortunately, the filter also decreased the returns from the particulate scatters along the path traversed by the lidar pulse. The passive reflector was painted with a black nonglossy paint to minimize the value of the receiver optical filter required for operation within the limits of detector linearity.

A pair of communication lines was installed between the lidar and aerosol chamber sites. One line was used for voice communication and the other line provided electrical impulses to the data recorders located near the chamber site at times of the lidar firing (see Appendix D).

The backscatter experiments normally consisted of making a series of lidar firings with a clean air chamber to establish the scattering properties of the background air and to check the lidar/chamber alignment. This was followed with alternating series of lidar firings for a chamber of clean air and various aerosol concentrations.

The data records collected at the lidar site for each laser firing included relative measures of:

- (1) Transmitted pulse peak power, P_t
- (2) Aerosol return, P_a
- (3) Passive reflector return, P_r .

The data records collected at the chamber site included:

- (1) A continuous strip chart record of the light transmission, T , for a path along the length of the chamber.
- (2) A continuous record of event marks indicating particle feeder disk rotation speed.

- (3) A record of event marks indicating time of lidar firing relative to the above data records.
- (4) A paper tape printout of transmission at times of the event marks of items (2) and (3) above.
- (5) A continuous record of relative 90° light scattering for times of low background light levels.
- (6) A "Nuclepore" filter sample of aerosol mass concentration, M, within various parts of the chamber for some lidar data collection periods.

Examples of the raw data records are shown in Appendix C, Figure C-5, and in Appendix G, Figure G-1. A detailed listing of the lidar and transmissometer data collected for each laser firing is given in Appendix H.

The lidar data records were used to evaluate the following quantities:

- (1) Relative aerosol backscatter uncorrected for variations of light energy transmission between the lidar and aerosol chamber.
- (2) Relative reflected energy from the passive reflector normalized by the transmitted peak power.
- (3) Relative aerosol backscatter corrected for variations of light energy transmission between the lidar and aerosol chamber by using the target reflected return.
- (4) Absolute aerosol backscatter from knowledge of the passive target reflectivity and lidar pulse length.
- (5) Absolute transmission of the laser energy across the aerosol chamber by using data from item (2) above and assuming a clean air transmission of 1.0.

The computational procedures used to derive these quantities are discussed in Appendix F.

The lidar-derived quantities of aerosol backscatter and extinction at the lidar wavelength were to be related to the white-light transmission

and aerosol mass concentration determined from the filter samples. However, as discussed in Appendix C, difficulties were encountered with deriving valid aerosol samples from the aerosol chamber. It was concluded that mass concentration evaluated from the particle feeder disk rotation speed was most representative of the aerosol within the chamber over an extended time period. Short term variations of the aerosol concentration were observed for the smaller sized fly ash fractions and they probably resulted from fly ash adhering to particle feeder components. Accordingly, the transmissometer output T was calibrated in terms of mass concentration M for each fly ash fraction by the expression:

$$T = \exp \left\{ - \left(\frac{\sigma}{M} \right) ML \right\} \quad (1)$$

where the volume extinction coefficient σ and M were determined from transmissometer data (L = transmissometer path length) and particle feeder disk rotation speeds averaged over extended time periods. A linear relation was observed between σ and M for each of the four fly ash fractions (see Appendix E). The experimental values of σ/M for each fly ash fraction were as follows:

<u>Fly Ash Fraction</u>	<u>σ/M^* (m^2/g)</u>
0 - 2.5 μ	0.943
2.5 - 5 μ	0.450
0 - 10 μ	0.336
5 - 10 μ	0.214

* The units of σ/M are given as m^2/g , which is numerically the same as the units $km^{-1}/mg\ m^{-3}$ or $km^{-1}/(mg/m^3)$.

The transmissometer reading at the time of each lidar firing was used to derive the instantaneous aerosol volume extinction coefficient and mass concentration. These values are tabulated with the lidar quantities in Appendix H.

C. Experimental Results

Data collected from the backscatter experiments are presented and discussed in this section. Experiments were conducted at two laser wavelengths using the SRI/EPA* Mark VIII ($0.7\ \mu$) lidar and the SRI Mark V ($1.06\ \mu$) lidar. The characteristics of these lidars are given in Appendix F.

Figure 3 shows aerosol backscatter quantities observed at the $0.7\text{-}\mu$ wavelength plotted against the optical volume extinction coefficients derived from the transmissometer data. The extinction coefficients may be related to plume opacity by the graphs in Figure 10 (shown later) for a plume length of 10 m.

Although a general increase of the volume backscatter coefficient accompanies increases of the optical extinction coefficient, an unexpected nonlinear relation exists at the higher concentration level. Lower values of backscatter than expected were observed at high aerosol concentrations. This can be caused by saturation (nonlinear response) of the optical detector and degradation of large peak signals by limited electronic bandpass. A third possible cause could be increased within pulse attenuation by the plume particulates at high particulate concentrations. Experiments conducted under laboratory conditions, although different from those used in the field experiment, indicate that detector saturation or electronic bandpass problems would not account for the degree of nonlinearity observed.

* Use of the Mark VIII lidar on this program was granted by the Division of Meteorology, Air Pollution Control Office, EPA.

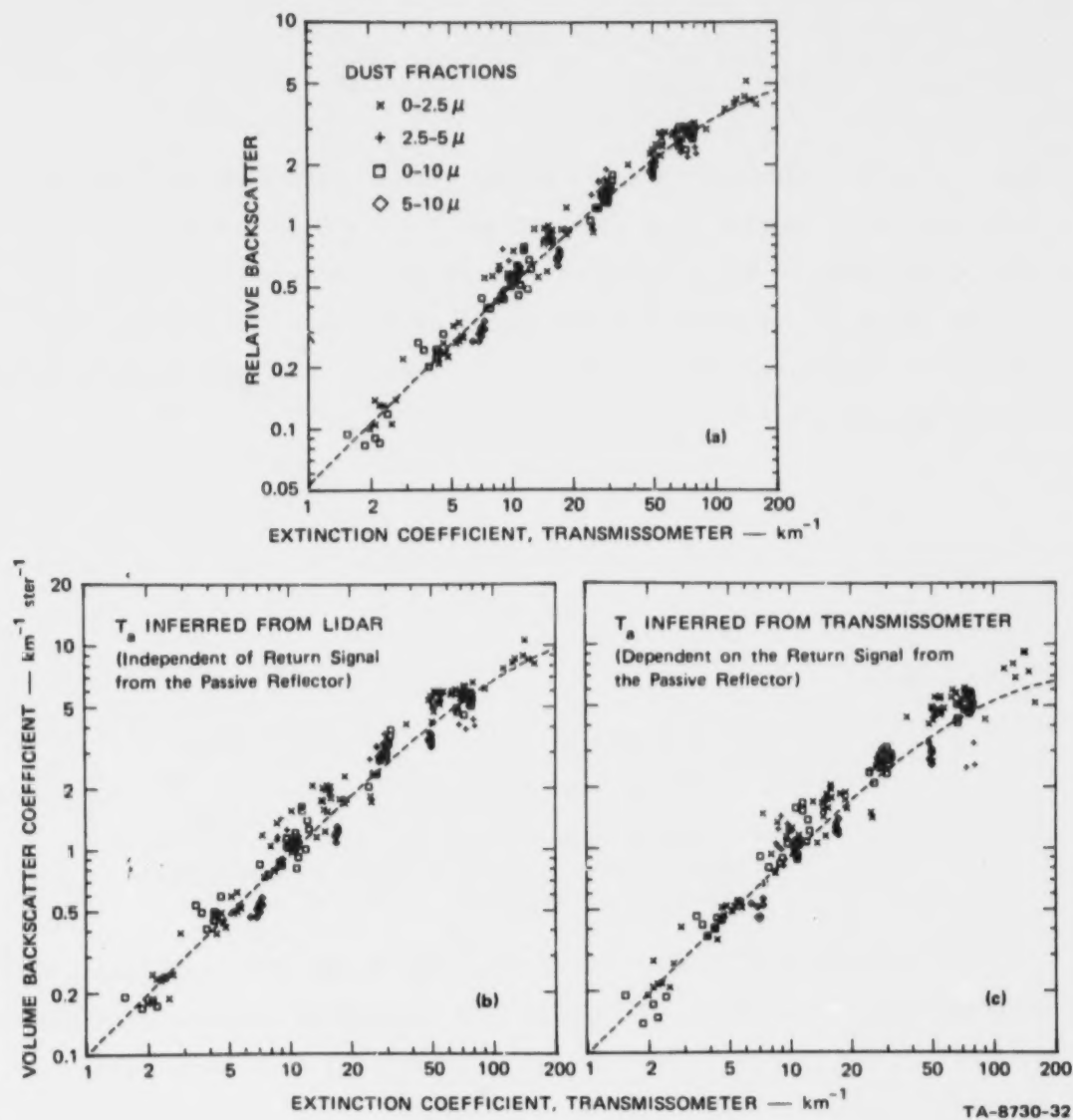


FIGURE 3 BACKSCATTER QUANTITIES OBSERVED AT 0.6943μ WAVELENGTH AS A FUNCTION OF THE EXTINCTION COEFFICIENT OBSERVED BY THE TRANSMISSOMETER

The fraction of signal decrease as a result of attenuation within the laser pulse by a homogeneous aerosol can be expressed as:

$$f = \frac{2}{\tau} \int_0^{\tau/2} e^{-2\sigma x} dx = \frac{1 - e^{-\sigma\tau}}{\sigma\tau}, \quad (2)$$

where τ is the pulse length and σ is the volume extinction coefficient. This expression reduces to a value of one for $\sigma = 0$ or for an infinitesimal pulse length. For a value of $\sigma = 100 \text{ km}^{-1}$ and $\tau = 0.01 \text{ km}$, $f = 1 - e^{-1} \approx .63$, which is approximately the amount of nonlinearity observed at $\sigma = 100 \text{ km}^{-1}$. The dashed lines in Figure 3 represent nonlinear least squares fit of the function:

$$Y = C_1 X \left(\frac{1 - e^{-C_2 X}}{C_2 X} \right), \quad (3)$$

where

Y = quantity plotted along the ordinate

X = quantity plotted along the abscissa

C_1, C_2 = parameters to be determined. C_1 will relate to the linear portion of the curve and C_2 will relate to effective pulse length.

The parameters C_1 and C_2 were determined by the nonlinear least-squares procedure of Marquardt (1963, 1964) using the supplied convergence criterion. The best fit function was determined by minimizing percent residuals; i.e., finding C_1 and C_2 so that $\hat{\Phi} = \sum_{i=1}^N [(\hat{Y}_i - Y_i)/Y_i]^2$ is a minimum, $\hat{\Phi}$, where $\hat{Y}$ is determined from the model for each of the N data points. The degree of fit of the model to the data points is objectively given as the standard error of estimate defined as $S_e = [\hat{\Phi}/(N - 2)]^{1/2}$.

The amount of data scatter varies among the backscatter quantities presented in Figure 3. This scatter can be caused by nonvalid assumptions made for the data analysis or by experimental errors. As more pieces of experimental information are included in the analysis, data point scatter may be reduced by eliminating certain assumptions or increased by the experimental errors associated with the additional information. The relative backscatter is simply the ratio of aerosol return to transmitted peak power; hence it ignores any variation during the experimental data collection of the atmospheric transmission characteristics along the 500-ft path between the lidar and aerosol chamber. However, both signals are relatively large and can be read from the primary data records (Polaroid prints) with little reading error. Mark VIII (0.7μ wavelength) data were collected where background conditions were similar so that variations of attenuation of the laser pulse along the 500-ft path were probably small. Most of the data point scatter in Figure 3(a) ($S_e = 0.16$) is thought to result from experimental limitations in deriving a valid measure of transmitted peak power or from variations in the peak-power-to-energy relationship; i.e., from variations in transmitter pulse shape (see Section IV B).

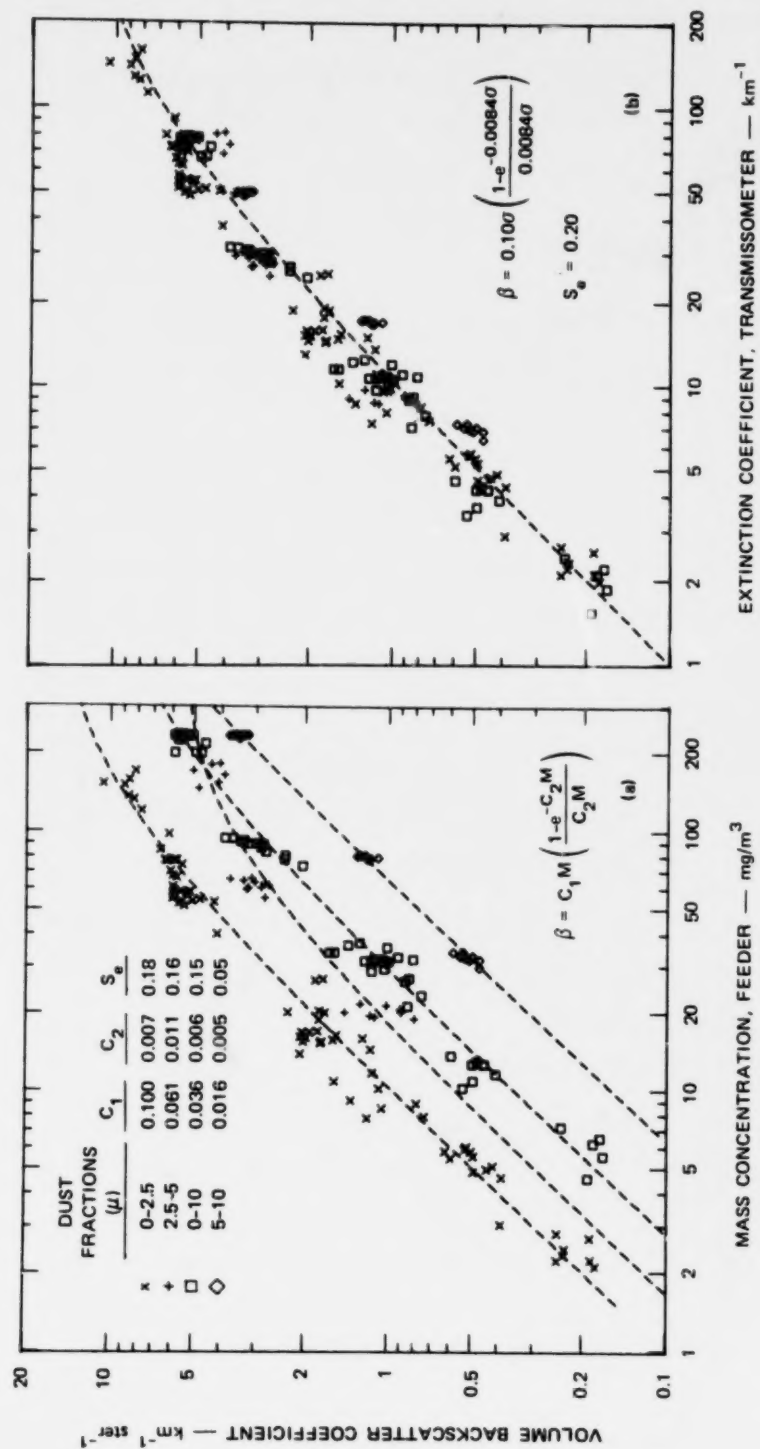
Volume backscatter coefficient, β , values are shown in Figure 3(b) and (c). The derivation of these data is discussed in Appendix G. Assumed in their derivation is knowledge of target reflectivity, laser pulse length, and transmission of the laser pulse by the test aerosol, T_a . As discussed in Appendix G, derivation of T_a from the lidar data results in an expression for β that is independent of the target reflected pulse P_r . In addition to information on relative backscatter, there is information in the form of lidar-observed quantities for conditions of a clear air aerosol chamber. The amount of data scatter in Figure 3(b) ($S_e = 0.20$) is slightly greater than that in Figure 3(a), which indicates that experimental errors associated with the additional information used

are greater than variations of clear air transmission during the experiments. Figure 3(c) shows volume backscatter coefficients derived by using T_a from the transmissometer data. Since wavelength dependence of transmission is relatively minor, the more accurate transmissometer values may have decreased the data scatter. However, in this analysis the target reflected energy pulse is required and is subject to large reading errors at high aerosol concentrations. This explains the large data point scatter ($S_e = 0.23$) at high aerosol concentrations in Figure 3(c).

In Figure 4(a) the volume backscatter coefficient is plotted against the particulate mass concentration as determined from the particle feed rates and in Figure 4(b) the volume backscatter coefficient is plotted against the extinction coefficient as determined from the transmissometer records [same plot as Figure 3(b)]. A greater nonlinear distribution of the 2.5-5 μ backscatter data is explained because these data, the first collected, produced lidar returns sufficiently large to be in the nonlinear response region of the lidar detector, and an additional neutral density filter was placed in the lidar receiver after this data run (see Appendix H). The other three fly ash fractions produced greater nonlinearity at higher concentrations in proportion to their backscattering efficiency at equal mass concentrations.

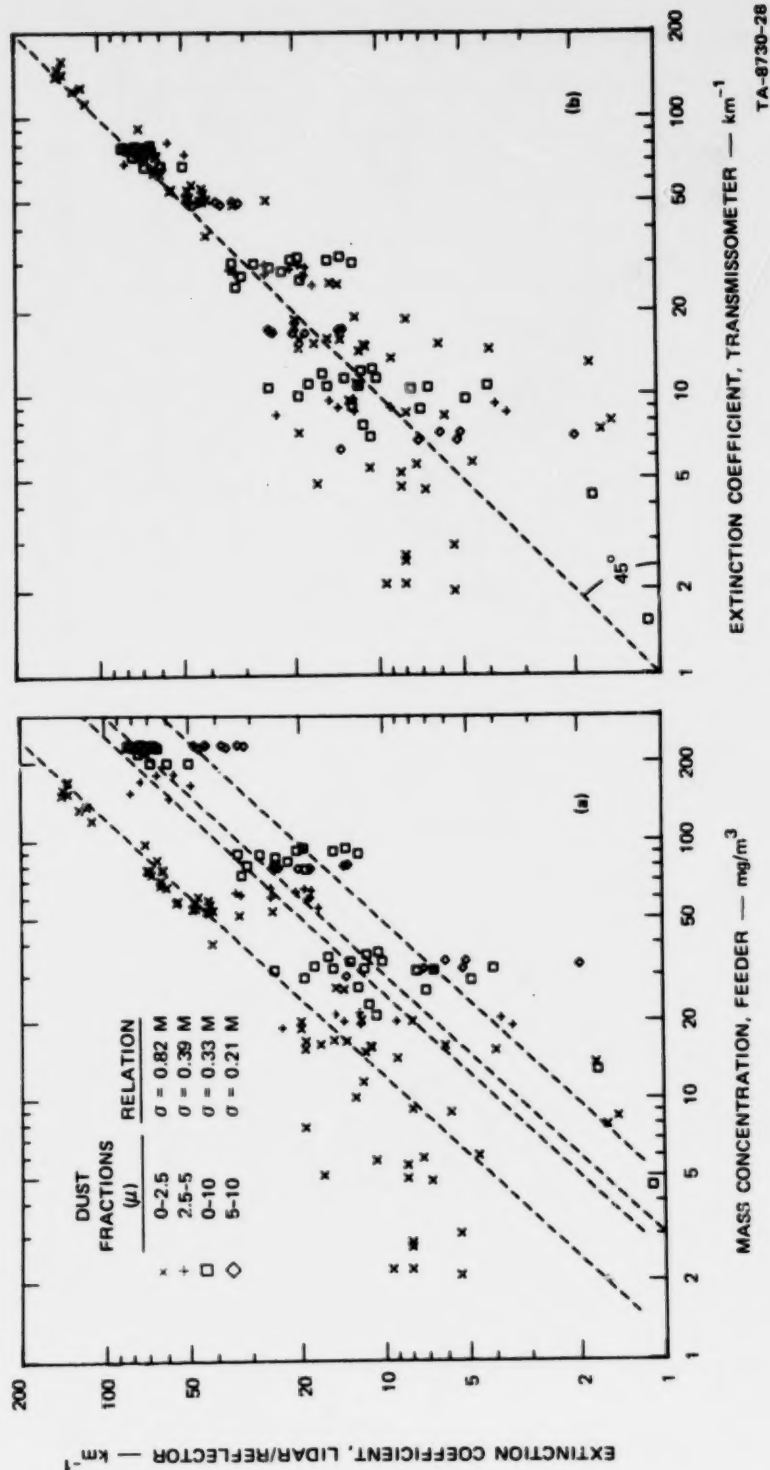
The data in Figure 4 indicate that the backscatter coefficient is nearly proportional to the optical extinction coefficient independent of particle size, but the relationship to particulate mass is dependent on particle size. This implies that at this lidar wavelength (0.7 μ) backscatter is proportional to second-moment quantities of the particle size distribution.

Figure 5(a) shows the volume extinction coefficient at a wavelength of 0.7 μ derived by relating the passive reflector return to the relative transmitted peak power (see Appendix G) as a function of particulate mass



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FIGURE 4 VOLUME BACKSCATTER COEFFICIENTS (β) OBSERVED AT A LIDAR WAVELENGTH OF 0.7μ RELATED TO PARTICULATE MASS CONCENTRATIONS (M) AND WHITE-LIGHT VOLUME EXTINCTION COEFFICIENTS (σ). The dashed lines represent the best fit to the data of the nonlinear equation indicated.



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FIGURE 5 VOLUME EXTINCTION COEFFICIENTS (σ) OBSERVED AT A LIDAR WAVELENGTH OF 0.7μ RELATED TO PARTICULATE MASS CONCENTRATIONS (M) AND WHITE-LIGHT VOLUME EXTINCTION COEFFICIENTS. The dashed lines represent the best fit linear relationship to the observed data.

concentration and Figure 5(b) shows the lidar derived volume extinction coefficient as a function of the optical volume extinction coefficient derived from the transmissometer records. The relationship of the extinction coefficient at $0.7\text{-}\mu$ lidar wavelength to mass concentration is about equally dependent on particle size as the relationship of backscatter to mass concentration [Figure 4(a)]. However, a greater overall scatter of the data points occurs with decreasing scatter for increasing particle concentrations. Since the largest experimental error associated with reading of the reflector return from the Polaroid records occurs at higher particle concentrations, the data scatter trend must be associated with the experimental technique and probably results from small variations of the clear air transmission that become negligible at large aerosol concentrations. The lidar-derived extinction coefficients ($0.7\text{ }\mu$) are only slightly less than optical (white light) extinction coefficients [Figure 5(b)].

Figure 6 presents volume backscatter coefficients derived with the $1.06\text{-}\mu$ wavelength lidar. Unfortunately, data were not collected for the $5\text{-}10\text{ }\mu$ fly ash fraction. Data on the relationship of volume backscatter to mass concentration were nearly half as dependent on particle size as data collected for the $0.7\text{-}\mu$ lidar wavelength [Figure 4(a)]. Correspondingly, the scatter of data points was greater in the plot of backscatter coefficient against optical extinction coefficient than the scatter of $0.7\text{ }\mu$ wavelength data (a standard error of 0.26 for the $1.06\text{-}\mu$ data is comparable to a standard error of 0.20 for the $0.7\text{-}\mu$ data, which included data from all four fly ash fractions). From Figure 6 it may be concluded that, for a lidar wavelength of $1.06\text{ }\mu$, the volume backscatter coefficient is more nearly related to particulate mass concentration independent of the particle size distribution than at the $0.7\text{-}\mu$ wavelength. Therefore, interpretation of single wavelength lidar data in terms of mass concentration is better achieved at $1.06\text{-}\mu$ wavelength than at $0.7\text{-}\mu$ wavelength.

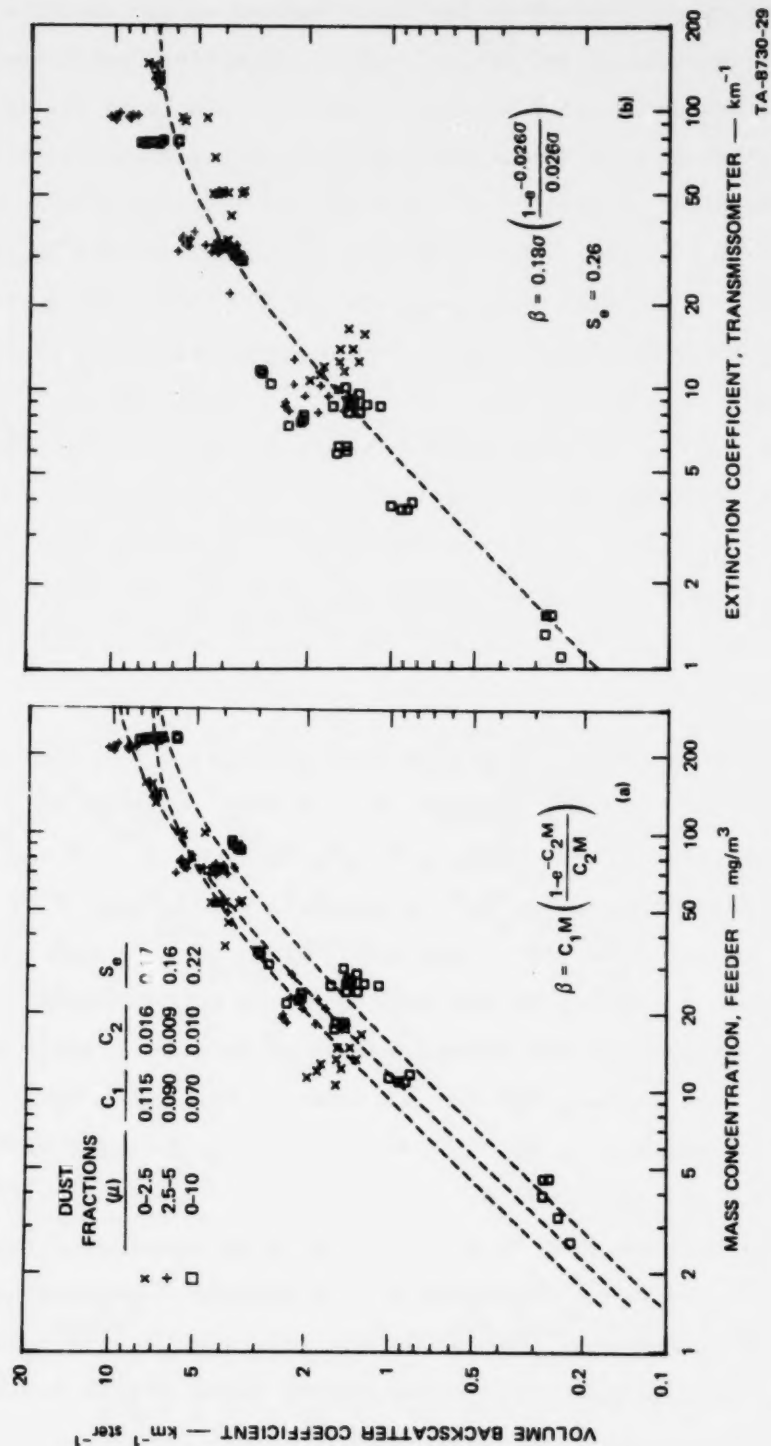


FIGURE 6 VOLUME BACKSCATTER COEFFICIENTS (β) OBSERVED AT A LIDAR WAVELENGTH OF 1.06μ RELATED TO PARTICULATE MASS CONCENTRATIONS (M) AND WHITE-LIGHT VOLUME EXTINCTION COEFFICIENTS (σ). The dashed line represents the best fit to the data of the nonlinear equation indicated.

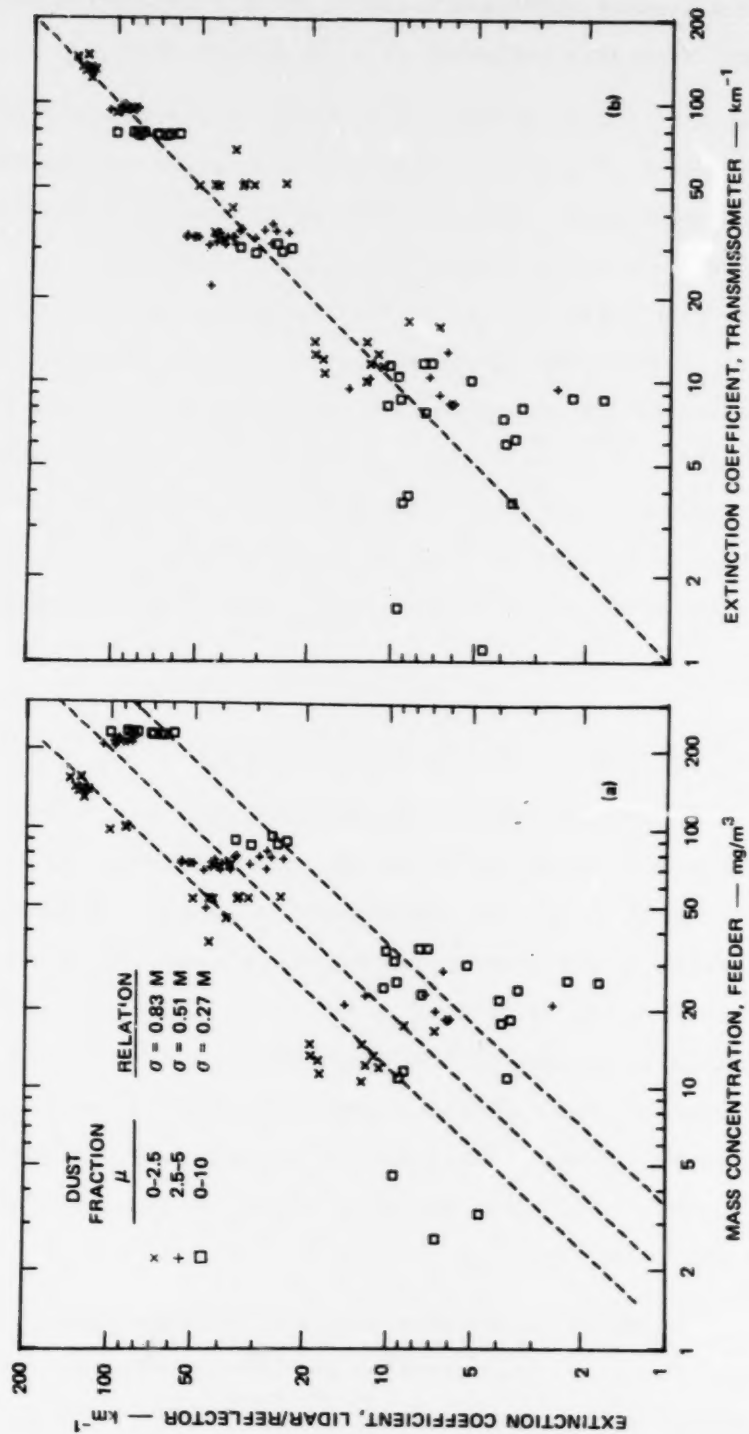
However, the best universal inference would be optical extinction (transmission or opacity) from data collected at a wavelength of 0.7μ .

Figure 7 shows the volume extinction coefficient derived at $1.06\text{-}\mu$ wavelength as a function of particulate mass concentration and the optical volume extinction coefficient. The empirical relationships between extinction and mass concentration are not substantially different from those derived at a lidar wavelength of 0.7μ . This indicates that extinction measurements taken at these two wavelengths with the same experimental accuracy as the measurements presented here could not be interpreted in terms of particulate mass concentration, as suggested by Twomey and Howell (1967). However, plume transmission measurements (by the technique of observing the clear air returns in front of and behind the plume) at either lidar wavelength may be related to white-light transmission or opacity.

D. Comparison of Experimental Results and Mie Theory

Individual particle backscatter cross sections and integrated or volume backscatter coefficients can be investigated theoretically using the exact Mie scattering theory for homogeneous or stratified spheres. Figure 8 shows results of Mie theory computation in terms of the backscattering efficiency, which is defined as the ratio of the computed backscatter cross section to the geometrical cross section. The particle size parameter is the ratio of the particle circumference to the wavelength of the scattered light. These results are for homogeneous particles with a real refractive index of 1.5 and imaginary refractive indices of 0.0 (nonabsorbing), 0.01, 0.05, and 0.10.

The sharp resonances of the nonabsorbing particles have been explained by surface waves, i.e., waves that travel along the interface between the sphere and the medium (Bryant and Cox, 1966; van de Hulst, 1957). It is



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FIGURE 7 VOLUME EXTINCTION COEFFICIENTS (σ) OBSERVED AT A LIDAR WAVELENGTH OF 1.06μ RELATED TO PARTICULATE MASS CONCENTRATIONS (M) AND WHITE-LIGHT VOLUME EXTINCTION COEFFICIENTS. The dashed lines represent the best fit linear relationship to the observed data.

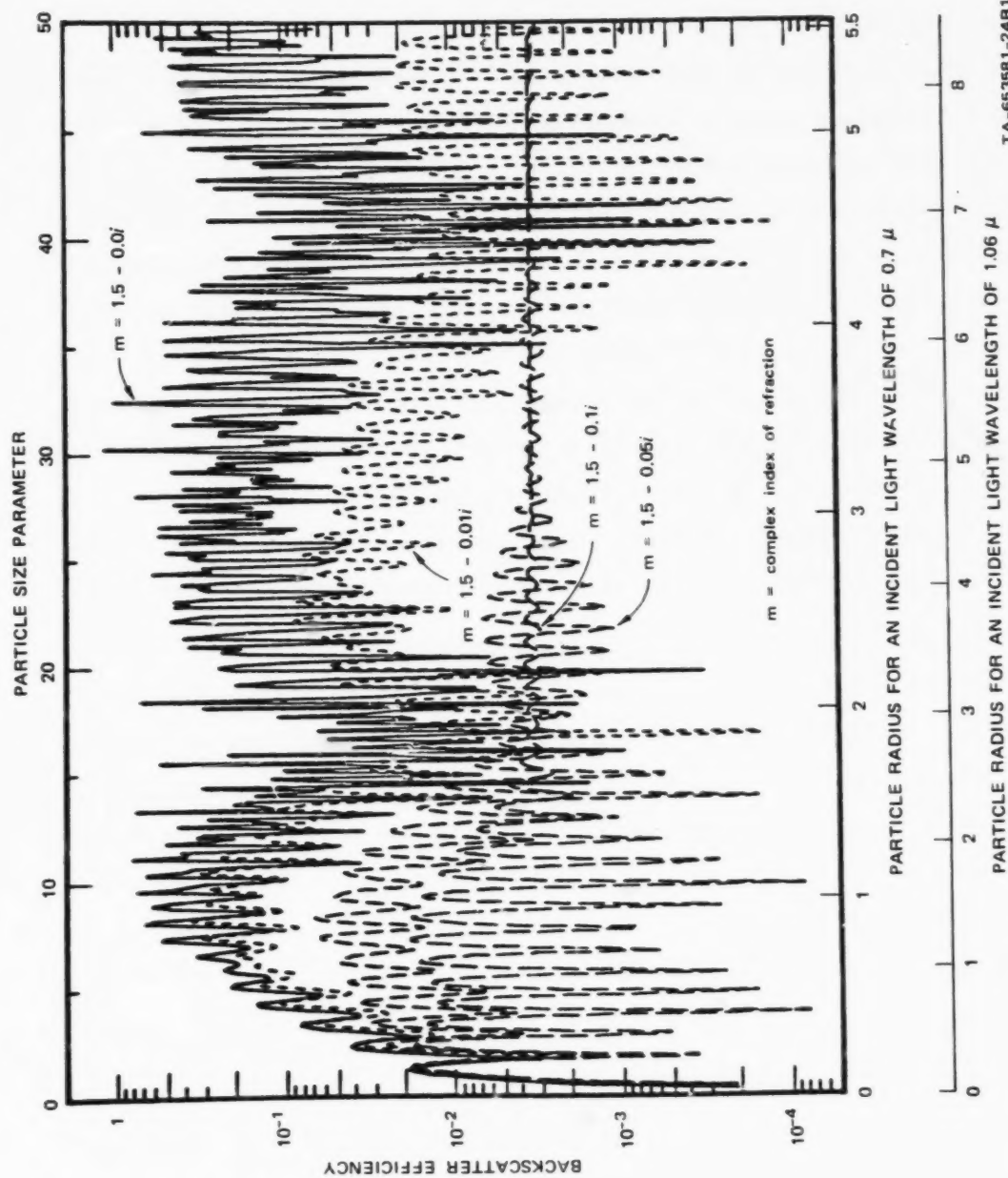


FIGURE 8 SPHERICAL PARTICLE (MIE THEORY) BACKSCATTER EFFICIENCY FACTORS (BACKSCATTER CROSS SECTION/GEOMETRICAL CROSS SECTION) AS A FUNCTION OF PARTICLE SIZE AT 0.7 AND 1.06 μ WAVELENGTHS FOR SEVERAL VALUES OF THE COMPLEX REFRACTIVE INDEX

seen that, as particle absorption increases (increase of the imaginary part of the refractive index), the magnitude of the resonances is decreased, as are the overall backscatter cross sections. However, with increasing absorption or increasing size, the backscatter approaches the Fresnel reflection limit at normal incidence (McDonald, 1962) and increases with increasing absorption by the particle. The important conclusion is that the absence of surface wave effects in the backscattered light from absorbing spheres could increase the correlation between volume backscatter and particulate concentration for small changes in particle size distributions. In addition, these surface waves are probably dependent on the smooth surface of the sphere for their propagation and thus may be absent within backscattered light from irregularly shaped particles regardless of their orientation. This conclusion is supported by the scattering measurements of Holland and Gagne (1970) on randomly oriented flat plates that gave less backscatter than equivalent size spherical particles.

The fly ash particulates used in the backscatter experiments were mostly all spherically shaped (see Appendix B), and hence theoretical results may relate favorably to empirical results. The ratios of volume backscatter coefficient to mass concentration and of volume extinction coefficient to mass concentration were experimentally determined for each fly ash fraction at each of the two lidar wavelengths (0.7 and 1.06 μ). Theoretically, these parameters, which are independent of particulate number densities, may be expressed as:

$$\frac{\sigma}{M} = \frac{\int_0^{\infty} \pi a^2 Q_e(x, m) n(a) da}{\int_0^{\infty} \frac{4}{3} \pi a^3 \rho n(a) da} \quad (4)$$

and

$$\frac{\beta}{M} = \frac{\int_0^{\infty} \pi a^2 Q_b(x, m) n(a) da}{\int_0^{\infty} \frac{4}{3} \pi a^3 \rho n(a) da} \quad (5)$$

where

a = particle radius

x = particle size parameter = $2\pi a/\lambda$

λ = incident light wavelength

m = complex refractive index

Q_e = extinction cross section/geometrical cross section

Q_b = backscatter cross section/geometrical cross section

ρ = particulate density

n = number of particles per unit volume per radius interval.

Values of σ/M and β/M were computed for each fly ash fraction at 0.7- and 1.06- μ wavelengths using a refractive index of 1.5-0.0 i and average log normal size distributions defined by the parameters presented in Appendix B, Table B-4. Because of the narrow backscatter resonances (Figure 8), the integrations were performed with an increment in the size parameter of 0.1, which is the increment of computation used for the data presented in Figure 8. The computational and experimental physical-optical parameters are listed in Table 1 for comparison. However, it must be remembered that the size distribution used to derive the theoretical values

Table 1
OBSERVED AND COMPUTED AEROSOL PARAMETERS

Size Fraction	"Average" Sauter Diameter			Observed White-Light Parameters		
	$\bar{D}_{32}$	$1/\bar{D}_{32}$	$(1/\bar{D}_{32})^*$	σ/M	$(\sigma/M)^*$	$Q_{e\text{ av}}$
0-2.5	1.7	0.59	1.00	0.943	1.00	2.73
2.5-5	3.1	0.32	0.55	.450	0.48	2.46
5-10	6.5	0.15	0.26	.214	0.23	2.12
0-10	4.0	0.25	0.43	.336	0.37	2.23

Size Fraction	Mie Theory Computations (0.7- μ wavelength)										
	σ/M	$(\sigma/M)^*$	β/M	$(\beta/M)^*$	K_e	K_b	k	$(k)^*$	$\bar{Q}_e$	$\bar{Q}_b$	$\bar{x}$
0-2.5	0.990	1.00	0.0820	1.00	0.411	4.96	12.07	1.00	2.76	0.228	7.70
2.5-5	.467	.47	.0410	.50	0.870	9.92	11.39	0.94	2.37	.208	14.01
5-10	.210	.21	.0151	.18	1.939	26.86	13.90	1.15	2.24	.161	29.44
0-10	.388	.39	.0295	.36	1.048	13.78	13.15	1.09	2.54	.193	18.09

Size Fraction	Mie Theory Computations (1.06- μ wavelength)										
	σ/M	$(\sigma/M)^*$	β/M	$(\beta/M)^*$	K_e	K_b	k	$(k)^*$	$\bar{Q}_e$	$\bar{Q}_b$	$\bar{x}$
0-2.5	1.157	1.00	0.0520	1.00	0.351	7.82	22.25	1.00	3.22	0.145	5.03
2.5-5	0.506	0.44	.0479	0.92	0.804	8.48	10.56	0.47	2.57	.244	9.17
5-10	0.217	0.19	.0160	0.31	1.877	25.40	13.56	0.61	2.31	.171	19.26
0-10	0.401	0.35	.0281	0.58	1.014	13.56	13.41	0.60	2.63	.184	11.84

Size Fraction	Lidar-Observed Aerosol Parameters													
	0.7- μ Wavelength							1.06- μ Wavelength						
	σ/M	$(\sigma/M)^*$	β/M	$(\beta/M)^*$	k	$Q_{e\text{ av}}$	$Q_{b\text{ av}}$	σ/M	$(\sigma/M)^*$	β/M	$(\beta/M)^*$	k	$Q_{e\text{ av}}$	$Q_{b\text{ av}}$
0-2.5	0.817	1.00	0.100	1.00	8.2	2.28	0.279	0.833	1.00	0.1145	1.00	7.28	2.32	0.319
2.5-5	.395	0.48	.0605	0.61	6.52	2.01	.308	.509	0.61	.0896	0.78	5.68	2.56	.456
5-10	.207	0.25	.0156	0.16	13.27	2.20	.166	--	--	--	--	--	--	--
0-10	.331	0.40	.0358	0.36	9.23	2.17	.235	.278	0.33	.0696	0.61	3.99	1.82	.456

$\bar{D}_{32}$ = Sauter diameter (μ)

σ = volume extinction coefficient (km^{-1})

β = volume backscatter coefficient ($\text{km}^{-1} \text{ster}^{-1}$)

M = mass concentration (mg/m^3)

$k = \sigma/\beta$ (ster)

$\bar{x} = \pi \bar{D}_{32}/\lambda$ = average size parameter

λ = wavelength (microns)

$\bar{Q}_e, Q_{e\text{ av}}$ = average extinction efficiency factor

$\bar{Q}_b, Q_{b\text{ av}}$ = average backscatter efficiency factor (ster^{-1})

K_e = K factor of Esser and Pilat (1971)

K_b = backscatter factor defined in the manner of K

$(P)^*$ = parameter P normalized to a value of 1.0 for the 0.2- to 5- μ fraction.

is an experimentally determined quantity and hence subject to experimental error, and that an accurate evaluation of the complex refractive index was not available.

Light extinction is not strongly wavelength dependent, and the σ/M values observed with white light may be related to the monochromatic computations. Especially good agreement exists between the white-light and 0.7- μ values for all four fly ash fractions. Hence, single wavelength lidar measurements of plume transmittance at 0.7- μ wavelength can be interpreted adequately in terms of plume opacity (1 - transmission of white light).

Parameters of Table 1 that have been normalized to a value of 1.0 for the 0-2.5 μ fly ash fraction are enclosed within parentheses. Quantities that are independent of size distribution are constant for each fraction; quantities that vary as the particle surface to volume ratio are proportional to the reciprocal of the Sauter diameter $\bar{D}_{32}$. As expected, the white-light and monochromatic extinction-coefficient-to-mass-concentration ratios vary nearly as the reciprocal of the Sauter diameter, $1/\bar{D}_{32}$. The computed ratios of backscatter coefficient to mass concentration at 0.7- μ wavelength show greater dependence on size distribution than the $1/\bar{D}_{32}$ variations and at 1.06- μ wavelength are nearly independent of size distribution for the 0-2.5 μ and 2.5-5 μ fly ash fractions. The 5-10 μ fraction is approximately half as dependent on size distribution as at the 0.7- μ wavelength. The observed ratios are in agreement with the computed ratios as far as establishing dependence on size distribution. Therefore, for the 1.06- μ wavelength both observations and theory predict less dependence on the backscatter-to-mass ratio on particle size than for the extinction-to-mass ratio (proportional to $1/\bar{D}_{32}$).

The other quantities presented in Table 1 are for comparison with the work of other authors. The value K_e , which is the ratio of particulate volume concentration to extinction coefficient, corresponds to the value K given by Ensor and Pilat (1971) and Pilat and Ensor (1970). The relationship between σ/M and K is given by

$$\frac{\sigma}{M} \left(\frac{\text{km}^{-1}}{\text{mg/m}^3} = \frac{\text{m}^2}{\text{g}} \right) = 1/K (\text{cm}^3/\text{m}^2) \rho (\text{g}/\text{cm}^3) \quad , \quad (6)$$

and the computation of K has assumed a fly ash density of $\rho = 2.46 \text{ g/cm}^3$ for each fly ash fraction (see Appendix B). The K_b quantities are the corresponding values for the ratios of particulate volume concentration to volume backscatter coefficient. Effective (average) efficiency factors for volume extinction and backscatter coefficients computed from Mie Theory are given by $\bar{Q}_e$ and $\bar{Q}_b$, where:

$$\bar{Q}_e = \frac{\int_0^\infty a^2 Q_e(x, m) n(a) da}{\int_0^\infty a^2 n(a) da}$$

and

$$\bar{Q}_b = \frac{\int_0^\infty a^2 Q_b(x, m) n(a) da}{\int_0^\infty a^2 n(a) da}$$

Observed average values of Q_e and Q_b are determined from the following expressions (Appendix E):

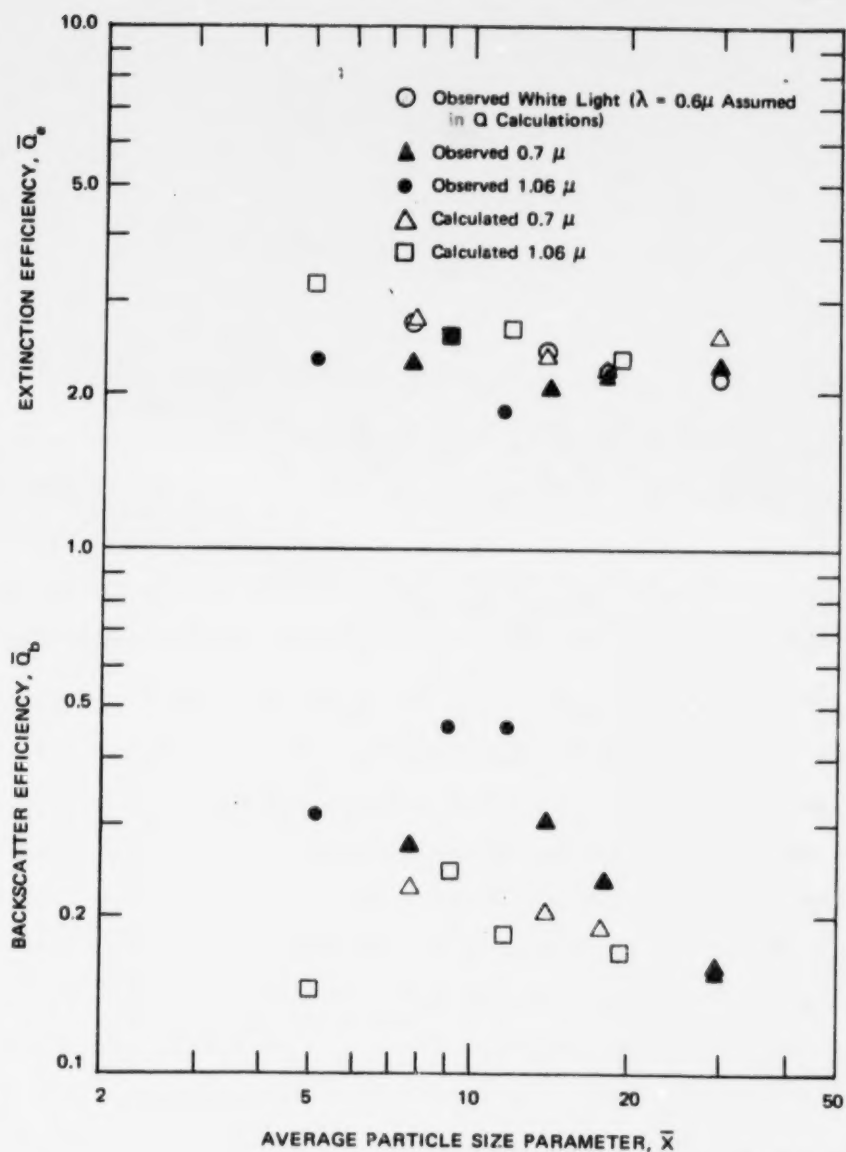
$$Q_{e_{av}} = \left(\frac{2}{3}\right) \rho \bar{D}_{32} \left(\frac{\sigma}{M}\right)$$

$$Q_{b_{av}} = \left(\frac{2}{3}\right) \rho \bar{D}_{32} \left(\frac{\beta}{M}\right)$$

where σ/M and β/M are experimentally determined values.

Figure 9 presents observed and computed backscatter and extinction efficiency factors as a function of particle size parameters computed from the Sauter diameters ($\bar{x} = \pi \bar{D}_{32} / \lambda$). The lidar-observed efficiency factors on the average are slightly less than the monochromatically computed factors, however they agree well with the observed white-light values.

The lidar-observed backscatter efficiency factors show a general maximum at a size parameter of approximately 10.0, which agrees with the maximum observed in the theoretical curves for single particles (Figure 8). The observed average values are greater than the computed average values and exhibit more of a peak at $\bar{x} = 10$, which indicates that the fly ash size distributions may have been more uniform (narrower) than assumed in the computations. However, the use of too large a target (passive reflector) reflectivity or too short a laser pulse length will produce overestimates of volume backscatter coefficients and backscatter efficiency factors. In any future work to derive these absolute backscatter quantities using the passive reflector technique, more emphasis must be placed on deriving knowledge of the target reflectivity and laser pulse length than was possible in the present study.



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FIGURE 9 OBSERVED AND COMPUTED EXTINCTION AND BACKSCATTER EFFICIENCY FACTORS AS A FUNCTION OF SIZE PARAMETER COMPUTED FROM THE AVERAGE SAUTER DIAMETERS

The relatively good agreement between theoretical and experimental results obtained gives support to the experimental procedures used during this study. Hence, further experimentation into areas for which existing theory is incomplete (such as scattering by irregularly shaped particles) may now proceed with some degree of confidence.

IV TECHNIQUES OF PLUME EVALUATION

A. Comparison of Opacity and Backscatter Measurement Techniques

Plume evaluation from a lidar backscatter signature consisting of the plume return, P_p , and near and far side clear air returns, P_N and P_F , are the subjects of the following discussion.

An inference of plume transmission, T , or opacity, O_p , from clear air returns is given by the expression:

$$O_p = 1 - T = 1 - \frac{R_F}{R_N} \left(\frac{P_F}{P_N} \right)^{1/2}, \quad (7)$$

where R is the range to the appropriate return signal. This equation assumes that backscatter coefficients for the clear air regions are equal and that the plume transmission at the lidar wavelength adequately represents the transmission of white light. However, this technique does not require absolute lidar calibration, and the inferred quantity is not subject to variations of clear air transmissions over the path from lidar to plume.

A plume opacity measurement is related to the volume extinction coefficient σ and the observed plume length L by Bouguere's law of attenuation:

$$\ln(1 - O_p) = -\sigma L. \quad (8)$$

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Figure 10 is a graphic presentation of this expression. [Aerosol opacity observed during the backscatter experiments may be determined from Figure 10 using the observed extinction coefficients (Section III) and a plume (chamber length) of 10 m.] From Eq. 8 opacity is related to the particulate mass concentration, M , of a vertically rising circular and homogeneous plume of radius a observed at ground level with a lidar elevation angle θ by the expression:

$$\ln (1 - O_p) = -\left(\frac{\sigma}{M}\right) Ma \sec \theta \quad (9)$$

The quantity σ/M is independent of particle concentration; it relates the aerosol optical density (the extinction coefficient σ) to its physical density M and may be considered a constant for particulates of a given type and relative size distribution. The relationship of this ratio to various particle refractive indices and log-normal size distribution parameters has been studied theoretically for spherical particles by Pilat and Ensor (1970), Ensor and Pilat (1971), and Conner and Hodgkinson (1967).

The total particulate emission M_t from the stack per unit of time may be expressed in terms of observed opacity as:

$$M_t = \pi a^2 M v = -\pi \left(\frac{M}{\sigma}\right) a \cos \theta v \ln (1 - O_p) \quad , \quad (10)$$

where v is the air speed of the stack emission. The interpretation of a lidar measurement of plume opacity in terms of particulate concentration, M , or total emission, M_t , requires knowledge of the optical-physical parameter σ/M and hence is dependent on the particle size distribution.

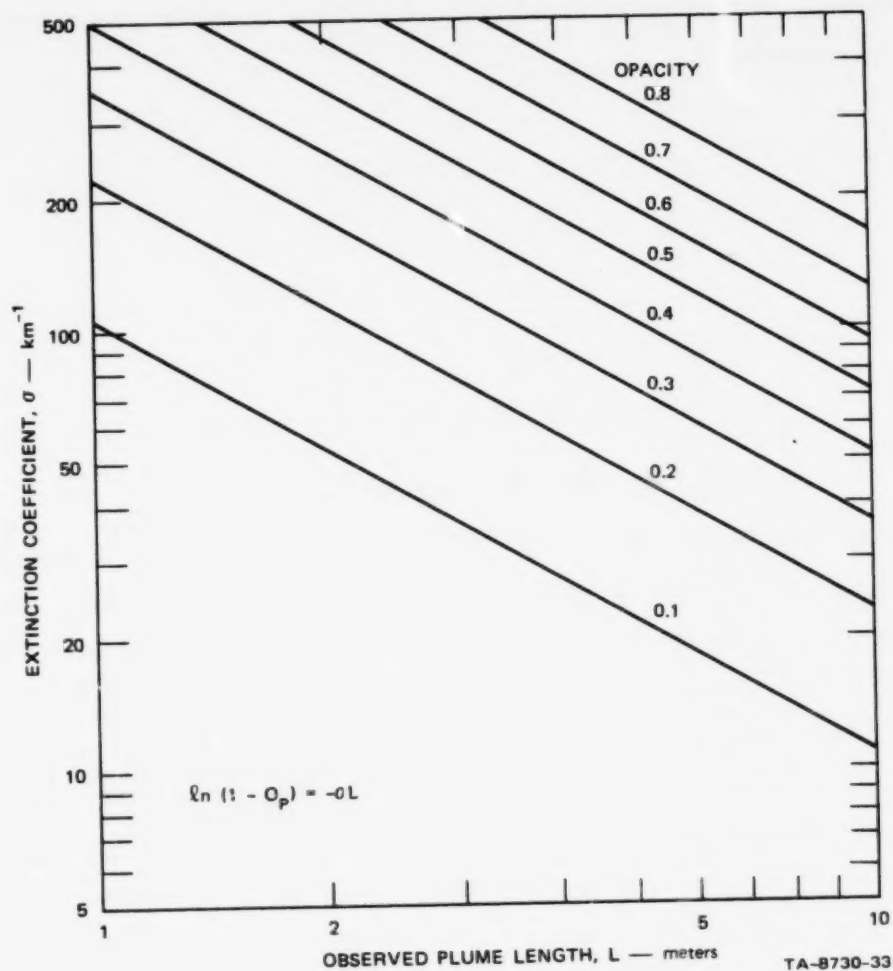


FIGURE 10 PLUME OPACITY AS A FUNCTION OF PARTICULATE VOLUME
EXTINCTION COEFFICIENT AND OBSERVED PLUME LENGTH

The lidar opacity measurement described above is independent of the lidar signal from the plume particulates, P_p (However, the large signals received from the plume may saturate typical lidar detectors and, without their complete recovery, accurate measurements of P_F may not be possible.) The plume return P_p may be related to plume mass concentration by the expression:

$$P_p = K R_p^{-2} \left(\frac{\beta}{M} \right) M T_c^2 \quad (11)$$

where

K = a lidar constant

T_c = clear air transmission to the plume

β = volume backscatter coefficient.

The above statements applied to the ratio σ/M also pertain to the quantity β/M . Equation 11 assumes that: particles are uniformly dispersed within the laser pulse; a constant energy density exists across the beam; attenuation by the plume particulates within the pulse may be neglected; and P_p is the maximum peak signal return, i.e., R_p is the range at which the pulse becomes completely embedded within the plume. As shown both experimentally and theoretically in Section III, the ratio β/M is nearly independent of particle size at long wavelengths. Therefore, less requirement is placed on knowledge of particle size for a mass concentration estimate based on a backscatter measurement than for one based on an opacity (transmission) measurement.

Other advantages of the plume particulate backscatter technique over the opacity technique are its adaptability to low density plumes and its ability to take a direct reading of plume mass concentration. In addition, because of the relatively large plume returns, less

expensive lidar instrumentation is required. However, disadvantages of the particulate backscatter technique are the requirement of an absolute lidar calibration, dependence of the plume return on the transmission of the laser pulse along the clear air path between the lidar and the plume return, dependence of the plume return on the emitted energy from the lidar, and the greater sensitivity of the volume backscatter coefficient than that of the volume extinction coefficient to particle shape and particle refractive properties. The above operational aspects of remote plume reading by observing backscatter of laser energy by the plume particulates requires further investigation.

B. Laser Pulse Length Considerations

The lidar data analyzed in this report are the peak power returns from both aerosol volumes and solid targets. The data presented give information on the scattering properties of aerosol volumes that is needed for the remote evaluation of plumes. These data have been presented in a manner that allows inferences about the accuracy with which remote plumes may be evaluated without knowledge of the particle size distribution. However, the experiments have been idealized in that the ratio of plume length to laser pulse length has remained nearly constant. Derivation of plume density (mass concentration) from opacity measurements requires information on the parameter σ/M and hence depends on particle size distributions. Backscatter has been shown to be less dependent on particle size distribution (for long wavelengths) and a more measurable quantity for low density plumes than either extinction or opacity.

The lidar equation for peak power returns may be expressed in general form as:

$$P(R_o) = \int_0^{\infty} Y(R) P_t (R_o - R) dR \quad , \quad (12)$$

where

$P(R_o) =$ peak power returned from range R_o

$Y(R) = KR^{-2}\beta(R)T^2(R)$

$P_t =$ power density

$K =$ a lidar constant.

When the pulse length is much less than the plume length ($L \ll L_t$), then $P(R_o) \approx Y(R_o) \int P_t(R_o - R) dR$. The instantaneous power return at a given range (R_o) is dependent on the transmitted energy $\left[\int_0^\infty P_t(R_o - R) dR \right]$ and the shape of the lidar backscatter signature is nearly that of the transformation function $Y(R)$. A feature in $Y(R)$, such as increased scattering by a stack plume imbedded within cleaner air, is reflected in the function $P(R)$. This case ($L < L_t$) relates to the backscatter experiments where it was assumed in the data analysis that:

$$\int_0^\infty P_t(R_o - R) dR = K^* P_t$$

where P_t is the observed peak transmitted power and K^* is a constant. The total area under the return signal (energy return) is given as

$$\int_0^\infty P(R_o) dR_o = K^* P_t \int_0^\infty Y(R_o) dR_o, \quad (13)$$

or the product of the pulse area and the area under the lidar backscatter signature (received signal as a function of range). Assuming Y is directly related to aerosol concentration, the return signal from a plume of greater density than its background may easily be distinguished from the background, and the range integration of the return signal from the plume

would relate to total concentration of the plume after applying a correction for attenuation by the plume particulates.

The pulse length may be larger than the plume it penetrates ($L \gg L_t$). In such a case Eq. (12) may be expressed as

$$P(R_o) \approx P_t(R_o - R) \int_0^{\infty} Y(R) dR ,$$

and the lidar signature is more responsive to pulse shape than $Y(R)$ variations. Hence, for long pulse lengths it is more difficult to distinguish the plume return superimposed on the background (clear air) return. In the extreme case of CW (continuous wave) lasers a single numerical value represents the return integrated over the observed path.

C. Polarization Measurements

Important inferences on the nature of scattering particulates can be made from polarization measurements of scattered light (Eiden, 1966; Gilbert, 1970; Dave, 1969; Harris, 1970). Since laser energy can be emitted as polarized light, it is questioned if polarization measurements of backscattered laser light can be used to derive particulate concentrations. The polarization of the incident light is conserved in the backscattered radiation from spherical particulates (except for circular polarized light that is conserved except for reversal of the rotation vector) and consequently is independent of the nature of the spherical particulates. Hence, any depolarization would be attributed to multiple scattering and would be relatable to particulate concentration. However, the polarization of the incident light tends to be destroyed in the backscattered light from irregularly shaped particles. Schotland et al (1971) has used this property to distinguish between water and ice clouds. Since

the primary backscattered light from smoke plume particulates would dominate over any multiple scattered light and since the particulates exhibit varying degrees of sphericity, it is unlikely that backscatter polarization measurements could be related to plume density. A limited number of polarization measurements made during this study showed no relationship between particulate concentration and depolarization of the energy returns. However, some experimental error was introduced because of the difficulty of making polarization measurements with coaxial lidar.

D. CW Laser Techniques

The present study indicates that optical backscatter techniques, along with existing lidar technology, may yield useful information on mass concentration within a stack plume. However, several characteristics of current lidar technology will tend to limit lidar's immediate usefulness as a practical, low cost, mobile monitoring instrument. The major limitations are: equipment complexity and cost, lack of a simple real-time data processor within the receiver, and high peak power optical radiation that could be hazardous to eye safety.

The cost of Q-switch crystal lasers (ruby, neodymium-glass, and neodymium-yag) currently used in lidar sensors is typically in the \$15,000 to \$20,000 bracket. Although these prices have declined somewhat in recent years as the result of improved technology and increased competition, it is unlikely that the price of Q-switched crystal lasers will decrease significantly in the near future. Accordingly, most Q-switched crystal lasers are expected to remain unattractive for this particular application in the foreseeable future.

In the present study extensive use was made of digital computer techniques to process the raw lidar data. For a truly practical monitoring instrument it is desirable that the lidar data be processed

automatically and analyzed in real time and that the result be displayed with little or no intervention by the operator. There seems to be no adequate device for this purpose, although recent advances in integrated circuits and memories may make feasible the use of hybrid analog and digital computation techniques at a comparatively low cost.

If these previously mentioned limitations can be overcome, the resulting device should be a relatively simple, low cost, mobile instrument that is capable of yielding accurate, repeatable measurements even when used by relatively unskilled personnel.

Application of CW lasers to the problem of remote evaluation of plume density may overcome the high cost and hazard to eye safety problems of Q-switched crystal lasers. Several CW laser techniques are briefly discussed below.

1. Unmodulated CW Laser System

The lowest cost and least sophisticated laser device for remote evaluation of plume densities would use an unmodulated CW laser as its energy source. The received backscattered signal would represent the backscattered light integrated over the viewing path. This is equivalent to path integration of the lidar backscatter signature from $R = 0$ to ∞ . Because of the inverse range-squared dependence of the lidar signature, the nearby clear air return in a relatively polluted atmosphere may equal the energy return by the remote plume. In addition, the range to the plume must be evaluated independently to correct for the range dependence of plume returns. Because of these problems an unmodulated CW laser backscatter device looks unattractive. However, spatial separation of the transmitter and receiver optics so that the receiver views only a remote portion of the complete scattering volume may eliminate the clear air scattering problem and give an estimate of plume range. A separation

distance of 8 to 10 ft between transmitter and receiver would allow the system to be mounted on a mobile van or stationwagon. Some effort may be expended, however, to align the system for a particular remote air volume, and the system optical stability may limit the accuracy of the plume reading. Another limitation is that the optical receiver would be required to detect weak backscatter signals in the presence of background sources such as the sun, street lights, and the like. Signal discrimination may be possible with an extremely narrow bandwidth optical filter or by modulating the CW laser with a constant frequency and including in the receiver electronics a narrow bandwidth electrical filter to reject the unmodulated background noise.

2. Pulse Modulation CW Laser System

An acousto-optic modulator suitable for helium-neon and argon lasers has been described by Maydan (1970). The modulator in effect allows a continuous wave helium-neon or argon laser to be operated in a pulsed mode with minimum pulse widths of 20 nsec and maximum pulse repetition rates of 2 MHz. In addition, approximately 50 percent of the power within the laser cavity is available at the output, thus increasing the peak power of the pulse by a factor of 50 to 100 over the corresponding CW power output of the same laser. The availability of a very high repetition rate laser transmitter makes it possible for the first time to use various signal-processing techniques within the receiver. Certain well-known techniques from microwave radar technology, such as signal-to-noise improvement by means of pulse-to-pulse averaging could be easily employed, along with hybrid analog and digital real-time processing of the resulting data.

The use of the acousto-optic modulator could, in theory, provide a number of significant advantages to lidar system performance. These

advantages could make possible low cost, remote monitoring of smokestack plumes. The acousto-optic modulator offers these major advantages:

- (1) It significantly increases the peak power output of a gas laser.
- (2) It provides the ability to pulse the gas laser very rapidly (typically, 10^6 pulses/sec).
- (3) It provides the ability to vary the width of the transmitted laser pulse.
- (4) The rapid pulsing of the laser transmitter produces a received signal with a rapid data rate (e.g., a million measurements of plume backscatter per second). This high data rate allows the use of range gating and video integration to increase receiver sensitivity and measurement accuracy over that derived using a single pulse.

When incorporated into a system, this technique may permit pulse (range) measurements to be made without any danger to eyes.

A simple system could incorporate the technique of automatically sending out a transmit pulse shortly after detecting a receive pulse from the plume. The rate at which the laser transmits pulses would be a function of the range to the plume. The strength of the receive pulses could then be corrected automatically for the range to the plume and recorded; the operator would be needed only for pointing and turning on the power switch. Other range discrimination techniques may be applicable and should be considered.

Although detailed system performance calculations have not yet been completed, preliminary calculations seem to indicate that this concept is worthy of further investigation.

3. FM CW Laser System

The FM CW technique (Jackson, 1971) provides the most complete set of capabilities and, with appropriate development, at little or no additional cost or complexity over the other CW laser systems. Ease of operation and eye safety features of CW systems are advantages of the FM technique. In addition, this technique has the lowest peak-power-to-average-power ratio and is not vulnerable to the receiver overload and recovery problems associated with pulsed systems. The sensitivity (hence, transmitted power required) of a radar depends on the average transmitted power and, for any given average power required from the laser, the FM technique results in the lowest peak power.

Calculations indicate that it will be possible to: modulate a low power CW laser beam; detect scattered laser light; and measure, in real time, the scattering as a function of range, thus deducing plume reflectance and plume opacity. The unique characteristic of the technique is that the laser beam is amplitude modulated by a frequency-modulated subcarrier. A telescope collects the light scattered by clear air and the plume, and a photodetector recovers the FM/CW subcarrier. The FM permits the measurement of range, signal strength, and range resolution by standard FM radar techniques. Real-time processing can be obtained using frequency filters and heterodyne techniques instead of the time-gating techniques applicable to pulse systems.

What is required at this time are experiments to obtain engineering data that will be needed in future FM/CW lidar development programs. These data (which are also required for other types of CW systems) will permit engineering choices to be made of system parameters such as subcarrier frequency, subcarrier FM rate, size and amplitude weighting of receiver aperture, frequency of sawtooth FM, laser type and power, laser stability specifications, and photodetector specification.

Of primary interest in the experiments will be optical Doppler spreading of the backscatter signal, conversion of laser FM noise into AM noise owing to the depth of the scattering region, and receiver aperture smoothing effects.

To summarize, the unmodulated CW laser system requires the least amount of electronics but provides the least amount of information required for plume evaluation. However, the optical alignment problems could outweigh the electronic simplicity for actual portable field systems. The pulse-modulated CW laser system could obtain, without an eye safety problem, the same data as a single-shot pulsed lidar. The FM/CW technique would require more development but could actually cost less and would provide a system capable of measuring both the backscatter and opacity of smoke plumes.

V RECOMMENDATIONS FOR FURTHER RESEARCH

The research conducted under this study has demonstrated that measurement of laser energy backscattered from plume particulates is useful for remote evaluation of smoke plumes and that evaluation of backscatter techniques is possible by using an especially designed aerosol chamber to generate an artificial plume consisting of known particulates at known concentrations. However, a low cost laser plume-reading instrument must still be developed and evaluated. In addition, the techniques used and the results obtained under this study suggest other research areas. Accordingly, it is suggested that research be undertaken to (1) develop a low cost plume reading instrument, (2) extend the experimental results of this study, and (3) further develop the aerosol facility for use in a variety of aerosol studies and instrument evaluations. In particular, the suggested areas of further research are:

- Development of a low cost remote plume sensor
- Experimental evaluation with other particulates
- Aerosol chamber improvement for aerosol studies
- Extend the accuracy of backscatter measurements made with pulsed lidars
- Computations from Mie theory
- Development of multiple wavelength lidar techniques.

Each of these recommended research areas is discussed in the following paragraphs.

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A. Development of a Low Cost, Remote Plume Sensor

Although high power lasers such as ruby (0.7μ) and neodymium-glass (1.06μ) were used to investigate backscatter from fly ash particulates, it is unlikely that these lasers will find extensive application for remote plume monitoring because of their high cost and complexity and their potential hazard to eye safety. Accordingly, further research should be directed toward applying the results and techniques of the present study to develop a low cost laser instrument for reading coal-burning power plant plumes. Experimental development of CW techniques based on bistatic, amplitude modulated and frequency modulated systems for remote plume reading is recommended. Preliminary evaluation of these laser systems could be accomplished using the experimental aerosol facility developed under this study.

B. Experimental Evaluation with Other Particulates

The present study dealt exclusively with fly ash particles. The results showed that optical characteristics could be characterized by a specific average particle size. Fly ash particles are mostly spherical in shape and heterogeneous in composition. It would be desirable to obtain optical data on other synthetic and real particulates to establish the effects of shape and composition as a guide to developing a generalized means for assessing the applicability of optical measurements. Examples of suggested synthetic powders, each of which has specific attributes, are: glass spheres, aluminum spheres, flake aluminum, Cab-O-Sil, iron oxide, ammonium chloride, dioctyl phthalate. Suggested actual industrial dusts are: cement, open hearth fume, paper mill recovery furnace dust, limekiln dust, sulfuric acid, and incomplete hydrocarbon combustion products.

Where feasible, it is proposed to grade the dusts by size, as was done in the present study, and to evaluate both closely sized fractions and composites.

C. Aerosol Chamber Improvement for Aerosol Studies

The present aerosol chamber provides a means of assessing laser backscatter measurements in terms of aerosol properties. In addition, a facility to generate large volumes of easily accessible aerosols consisting of known particles at known concentrations would be useful for a variety of other studies including:

- Evaluation of techniques of deriving a valid aerosol sample
- Evaluation of direct aerosol samplers
- Comparison of various sampling instruments
- Development of optical aerosol sensors such as multiwavelength transmissometers and multiangle photometers
- Investigation of multiple scattering effects on instrument response functions.

It is recommended that the aerosol chamber be further developed to provide a unique facility for both remote and direct aerosol studies. Some improvements include:

- The dust feeder system should be modified to produce a more uniform particulate feed rate.
- Distributors should be placed at the chamber inlet to straighten air flow within the chamber.
- The problem of deriving representative aerosol mass concentration should be resolved.
- The present optical systems should be modified to eliminate drift in transmissometer readings and permit angular scattering measurements during daylight hours.

- Instrumentation should be added to provide the aerosol size distribution measurements.

D. Extending the Accuracy of Backscatter Measurements
Made with Pulsed Lidars

High powered Q-switched ruby and neodymium-glass lasers were used to collect aerosol backscatter data for this study. The accuracy of such data could be significantly improved by better monitoring of the transmitted peak power and the total energy of the laser pulses, and by better knowledge of the target reflectivity at lidar wavelengths used.

Most Q-switched ruby and neodymium-glass lasers exhibit significant pulse-to-pulse variations in output power and energy. In a well-designed laser cavity, the pulse shape of the laser output is approximately Gaussian and does not exhibit a significant pulse-to-pulse variation. The major pulse-to-pulse variations occur in the peak power output of the laser. For the present study, the peak power was monitored by means of a beam splitter that directed a small portion of the output pulse onto a diffusing surface that was viewed by a fiber optic light pickup coupled to the receiver optics. The output energy was assumed proportional to the peak power; i.e., it was assumed that the pulse shape remained constant. The use of improved calibration techniques for assessing transmitted energy should result in greater accuracy of the backscatter measurements.

The laser energy reflected from a solid target of known reflectivity was used in this study to derive an absolute value of the volume backscatter coefficient. A black target was used rather than a standard white target in order to reduce the target return to a level of the detector response that is linear. In future backscatter experiments using this technique, more emphasis must be placed on evaluating the target reflectivity at each lidar wavelength used.

E. Computations from Mie Theory

Actual aerosols consist of various sized particles rather than particles of a single size. However, it is possible to characterize every phenomenon by some effective average particle size. The effective size will be different for different phenomena. It is desirable to establish what average size will characterize each of the common optical phenomena that may be used to determine physical aerosol characteristics: transmission, forward scattering, backscattering, and 90° scattering. This can be done from the Mie theory for spherical particles. Although it is recognized that such calculations may not apply to the irregularly shaped particles encountered in practice, such theoretical evolutions would be of tremendous use as a guide to the type of engineering approximation that might be useful for assessing the optical properties of such actual systems. In the present study, for example, experimental results indicated that the Sauter diameter, $\bar{D}_{32}$, was a good characteristic measure of the transmission effects. This was also confirmed by a few spot theoretical calculations based on Mie theory. For backscatter, Mie theory predicts multitudinous and abrupt changes of intensity with particle size; however, for typical particle size distributions, such variations tend to be evened out rapidly so that the aerosol backscatter may be related to an average particle size.

It is suggested, therefore, that calculations for spherical particles be carried out for various optical phenomena at various wavelengths, particle refractive indexes, and particle size distributions. The aerosol optical parameters should then be related to aerosol physical properties.

F. Development of Multiple Wavelength Lidar Techniques

The results of this study suggest that multiple wavelength lidar measurements may provide more valid estimates of particulate concentration than single wavelength lidar measurements. It is suggested that the two-wavelength lidar data presented in this report be used to investigate

techniques of inferring higher moments of the size distribution from such measurements. Also, since the Mie theory computations relate well to experimental data for fly ash particulates, it is suggested that the Mie theory be used to investigate various aspects of multiple wavelength lidar probing of plume particulates. The number and position of wavelengths used and the manner of combining the measurements for an inference of particulate concentration could be investigated by this means at relatively low cost.

REFERENCES

- Bryant, H. C., and A. J. Cox, 1966: Mie theory and the glory. J. Opt. Soc. Am., 56, 1529-1532.
- Conner, W. D., and J. R. Hodgkinson, 1967: A study of the optical properties and visual effects of smoke-stack plumes. Cooperative Study Project, Edison Electric Institute and U.S. Public Health Service.
- Cook, C. S., G. W. Bethke, and W. D. Conner, 1971: Development of a mobile lidar system to measure smoke plume opacity, paper presented at the Joint Conference on Sensing of Environmental Pollutants, Palo Alto, California, November 8-10, 1971.
- Dave, J. V., 1969: Scattering of visible light by large water spheres. Applied Optics, 8, 155-164.
- Eiden, R., 1966: The elliptical polarization of light scattered by a volume of atmospheric air. Applied Optics, 5, 569-576.
- Ensor, D. S., and M. J. Pilat, 1971: Calculation of smoke plume opacity from particulate air pollutant properties. J. Air Pollution Control Association, 21, 496-501.
- Evans, W. E., 1967: Development of lidar stack effluent opacity measuring system. Final Report, Edison Electric Institute, SRI Project 6529, Stanford Research Institute, Menlo Park, California.
- Gilbert, G. D., 1970: The effects of particle size on contrast improvement by polarization discrimination for underwater targets. Applied Optics, 9, 421-428.
- Harris, F. S., 1970: Water-and-ice cloud discrimination by laser-beam scattering. Paper presented at the 1970 Spring Meeting of the Optical Society of America.
- Holland, A. C. and G. Gagne, 1970: The scattering of polarized light by polydisperse systems of irregular particles. Applied Optics, 9, 1113-1121.

- Jackson, D. W., 1971: New development of a CW laser radar. Paper presented at Joint Conference on Sensing of Environmental Pollutants, Palo Alto, California, November 8-10.
- Marquardt, D. W., 1963: An algorithm for least-squares estimation of nonlinear parameters. J. Soc. Ind. Appl. Math., 11, 431-441.
- Marquardt, D. W., 1964: Least squares estimation of nonlinear parameters. IBM Computer Library SHARE program 3094.
- Maydan, D., 1970: Fast modulator for extraction of internal laser power. J. of Applied Physics, 41, 1552-1559.
- McDonald, J. E., 1962: Large-sphere limit of the radar back-scattering coefficient, Quart. J. Roy. Met. Soc., 88, 183-186.
- Pilat, M. J., and D. S. Ensor, 1970: Plume opacity and particulate mass concentration. Atmos. Environment, 4, 163-173.
- Schotland, R. M., K. Sassen and R. Stone, 1971: Observations by lidar of linear depolarization ratios for hydrometeors. J. Applied Meteorology, 10, 1011-1017.
- Twomey, S., and H. B. Howell, 1965: The relative merit of white and monochromatic light for the determination of visibility by back-scattering measurements. Applied Optics, 4, 501-506.
- Twomey, S., and H. B. Howell, 1967: Some aspects of the optical estimation of microstructure in fog and cloud. Applied Optics, 6, 2125-2131.
- van de Hulst, H. C., 1957: Light scattering by small particles. John Wiley and Sons, Inc., New York, New York.

Appendix A

DETAILS OF THE SIGHTING TUNNEL SYSTEM

Details of the sighting tunnel system, diagrammed in Figure 1 of the main text, are discussed in this appendix. A photograph of the system is shown in Figure A-1.

Air was supplied by means of a Buffalo Forge Type BL, Model No. 365, Arrangement 9, Class II centrifugal blower, belt driven at 2,080 rpm by means of a 5-hp motor. This blower discharged into the horizontal duct system shown in Figure A-2. The pressure difference across the 12-in.-diameter nozzle located after the blower was used to measure fan air flow rate.

Dust Feeder

Dust was metered out by a proprietary grooved-disk feeder. The dust feed rate was determined by the size of the groove and the disk rotational speed. The dust was exhausted pneumatically from the groove and fed into the sonic velocity stream as shown in Figure A-3. This sonic stream also provided the suction for pulling conveying air through the feeder. The pressure upstream of the sonic nozzle was 50 psig during a normal run. The compressed air flow was calculated as 33 CFM and the induced feeder conveying air was estimated to be on the order of 2 CFM.

Separate feeder calibrations were carried out to establish the feed rate as a function of disk speed for each dust. These were conducted by pressurizing the feeder with a metered amount of compressed air (1.3 CFM) that carried the dust from the groove into a separate collecting bag. The

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collecting bag was weighed over timed intervals. The results of these calibrations are shown in Table A-1. The dust feed rate was usually linear with disk speed; in these cases the average value of the grams/revolution measured at all dust speeds was used in all subsequent calculations of feeder rates. In a few cases a significant variation in grams/revolution was observed; thus no average value is shown for them in Table A-1, and the calibration factor established for each disk speed was used in subsequent calculations.

Special tests were conducted to observe the effect of the compressed air pressure on dust dispersion. In the tests the transmissometer reading was recorded on a strip chart for a timed interval as the compressed air pressure was changed in steps for a given feeder disk speed setting. Typical results are shown in Table A-2. The test results would indicate that a reproducible state of dust dispersion is obtained for pressures over 30 psig. At lower pressures the apparent dispersion is progressively poorer, as reflected by the greater transmissometer readings. The sharp drop in apparent dispersion at pressures below 30 psig for the speed control setting of 100 was partially due to a failure of the feeder groove to be unloaded completely at that speed because of the lower induced air at the lower air pressures. At a speed control setting of 40 or less, the groove was essentially unloaded at all air pressures. Even at a setting of 100, no more than 20% of the groove was not unloaded. Thus, any increase in transmissometer reading must reflect primarily the effect of dust dispersion and not any actual reduction in dust feed rate.

Aerosol Chamber

The dust-laden air stream is gradually decelerated in the expanding ductwork and allowed to enter the plenum chamber beneath the sighting tunnel. In the original equipment Arrangement A, the top of the plenum

chamber was equipped with three rectangular nozzles pointing upward. Two were at either end as shown in Figure A-2. These two nozzles each had a throat dimension of 3 in. x 20 in. The third nozzle was located in the center and had a throat dimension of 2 in. x 20 in. The sighting tunnel was filled with a controlled aerosol by the dust-laden air coming into it through the central nozzle. The two end nozzles served as an aerosol curtain to carry away any outside air blown into the tunnel and hence to establish a fixed boundary to the dust-laden air through which the lidar would sight.

Because sampling problems had become obvious in the first few runs, the central nozzle was replaced after Sampling Run 8 with the multihole distributor shown in Figure A-2 to minimize any effects on sampling that the high velocity from the central jet might have. This arrangement (Arrangement B) was used throughout the rest of the study.

Air Rates

With Arrangement A the air flow could be measured by either the pressure differences across the 12-in. nozzle after the fan or by the drop across the rectangular nozzles. The total flow measured by these two methods agreed within 2%. The pressure drop across the plenum chamber nozzles was slightly less with Arrangement B than with Arrangement A and the system air flow increased slightly (approx. 2%) for Arrangement B. The total flow with Arrangement B was taken as 5800 CFM, including compressed air introduced at the feeder. It is believed that this value should be correct within $\pm 3\%$; the value also agrees well with the flow to be expected from the fan performance curve provided by the manufacturer. Although the air flow through the system could have been varied by providing a throttle at the fan inlet, this was not done. All data were taken at this same flow rate. The flow rate also changed slightly with air

temperature. Since this variation should have been less than $\pm 3\%$, it was not allowed for. Because air rate variations with temperature were also not allowed for in the sampling system, the effect of temperature is largely self-compensating in so far as overall concentration comparisons are concerned.

Flow Pattern

The air flow pattern in the sighting tunnel was established qualitatively by probing with short streamers on a rod. Apparently a marked rotary circulation in the tunnel is induced because the entrance to the plenum chamber is located on one side. The central 55-hole distributor alone is apparently not sufficient to eliminate the side velocity component. Viewed from the inlet end (east end) of the tunnel, the rotary flow was clockwise in both halves of the tunnel.

Dust Deposition

During the course of the test two inspections were made of the inside of the aerosol chamber system by disconnecting the 4-ft $\times$ 18-in. transition piece. In both cases it was observed that there was an obvious deposit on the floor of the plenum chamber, the sighting tunnel, and the transition piece. The sidewalls and roof had only a slight coating that was negligible compared with that on the floor. The ductwork upstream of the transition piece and including the 3-ft upstream portion of the transition piece was essentially totally void of any dust deposit.

In the inspection on February 2, 1971 (after Sampling Run 8), a portion of the deposit on the floor of the transition piece was collected by brushing and was weighed. The weight indicated a deposit density of approximately $(1/3)$ gram/sq ft. Because this was the region of heaviest deposit, it was estimated that the deposit in the entire chamber system

totalled less than 50 g. Since this represented the entire accumulation after an estimated 2 to 3 lb of dust had been fed to the system, it may be concluded that wall deposit within the chamber amounted to less than 5% of the dust feed. These measurements were made rather crudely, however, and it was possible that the (1/3) gram/sq ft value was low because of windage losses.

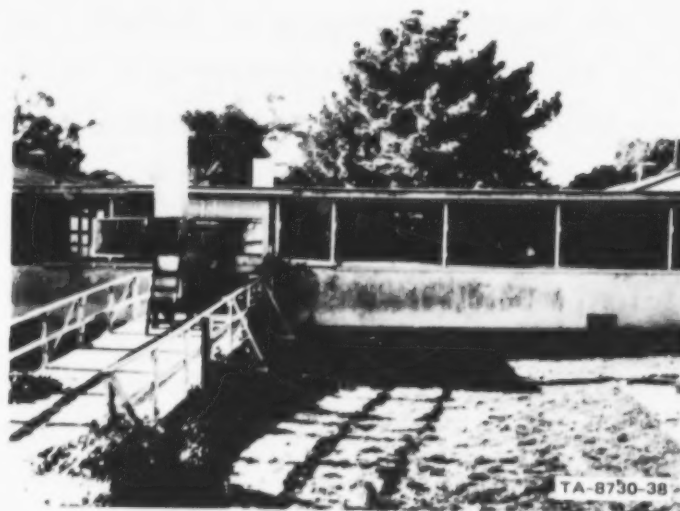
On October 4, 1971, the chamber was opened for the second time and was cleaned out completely with a small hand-vacuum cleaner. The dust from the various parts of the system was collected separately in a bag filter and weighed. The results are shown in Table A-3. These measurements also indicated that less than 5% of the dust feed was retained on the chamber system walls.

The material collected on both of the above occasions had a Fisher diameter (corrected for slip flow) of 6.7 and 6.0 μ , respectively. Examination under the microscope showed it to be substantially all in the 5- to 10- μ range.

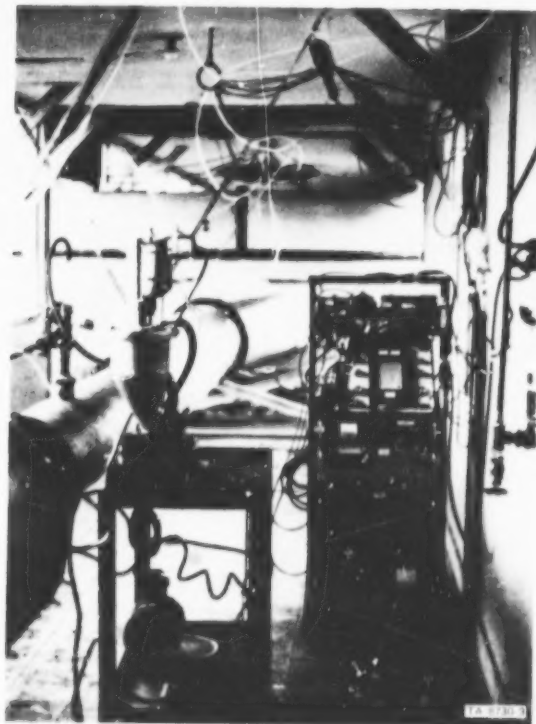
Because the chamber was subject to random vibrations and to deliberate rapping during the experimental program, it is not possible to be certain that a greater wall deposit had not accumulated but was dislodged because of this mechanical action. Considering the low velocities (4 to 8 ft/sec) in the various parts of the chamber, it is not likely that significant reentrainment of deposited dust occurred.

Transmissometer

A transmissometer was mounted in the sighting tunnel. The collimated beam generator or light source was located at the upper right of the inlet end of the tunnel and the detector at the lower left end of the outlet end. Both light source and detector were located outside the aerosol zone in ambient air. The transmissometer details are given in Appendix D.

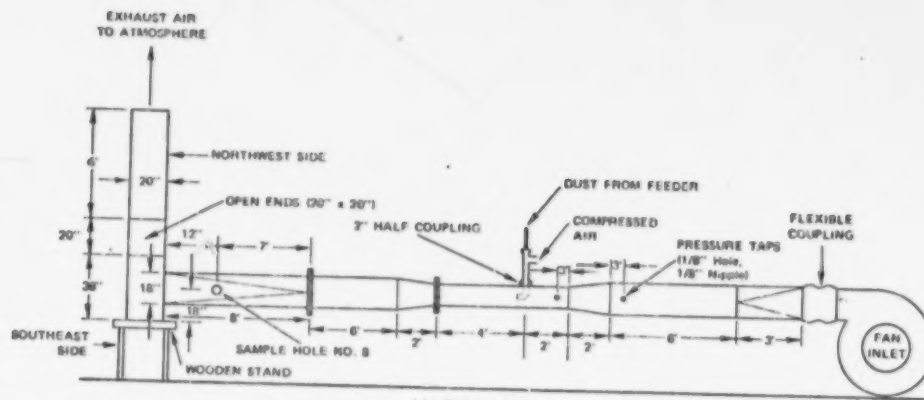


(a) FRONT VIEW OF AEROSOL CHAMBER SHOWING
LASER PULSE ENTRANCE

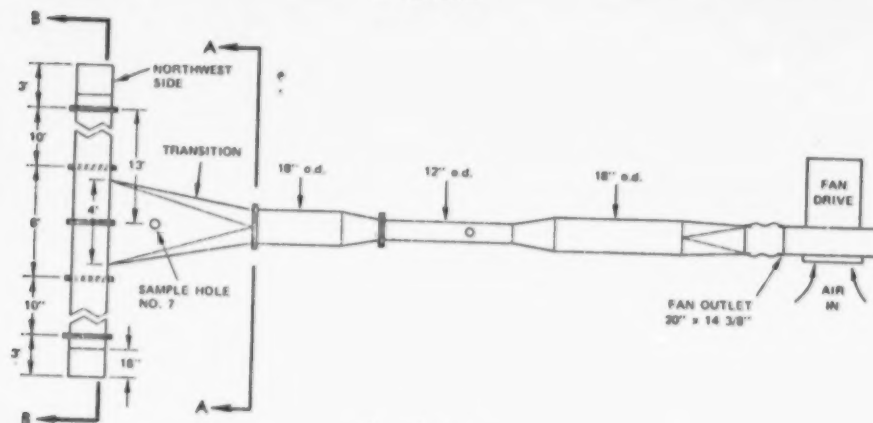


(b) SIDE VIEW OF AEROSOL CHAMBER WITH
PARTICLE FEEDER AND INSTRUMENTATION
FOR THE OPTICAL SENSORS

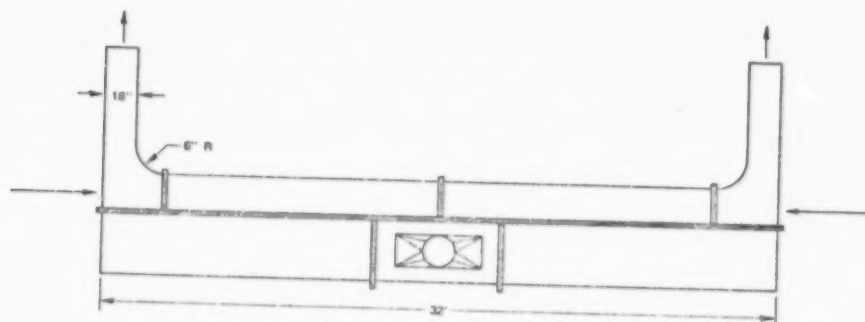
FIGURE A-1 AEROSOL CHAMBER USED IN THE BACKSCATTER EXPERIMENTS



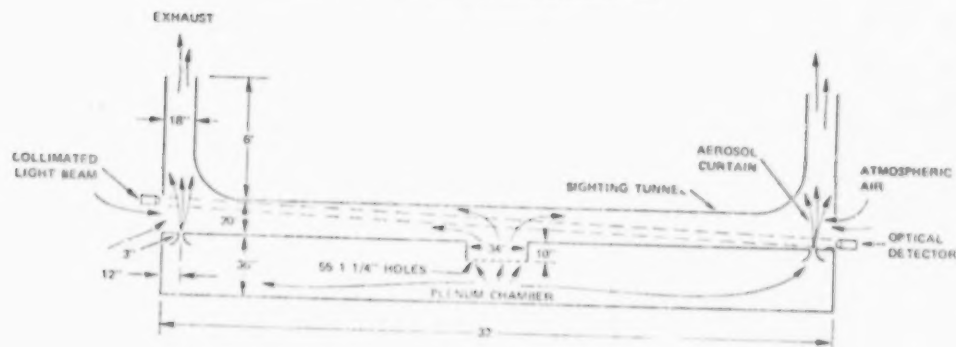
(a) ELEVATION



(b) TOP VIEW



(c) INSIDE ELEVATION OF TUNNEL (Section A-A, Northwest Side)



(d) SECTIONAL VIEW OF CONTROLLED AEROSOL CHAMBER (Section B-B)

FIGURE A-2 AEROSOL CHAMBER DETAILS

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A-9

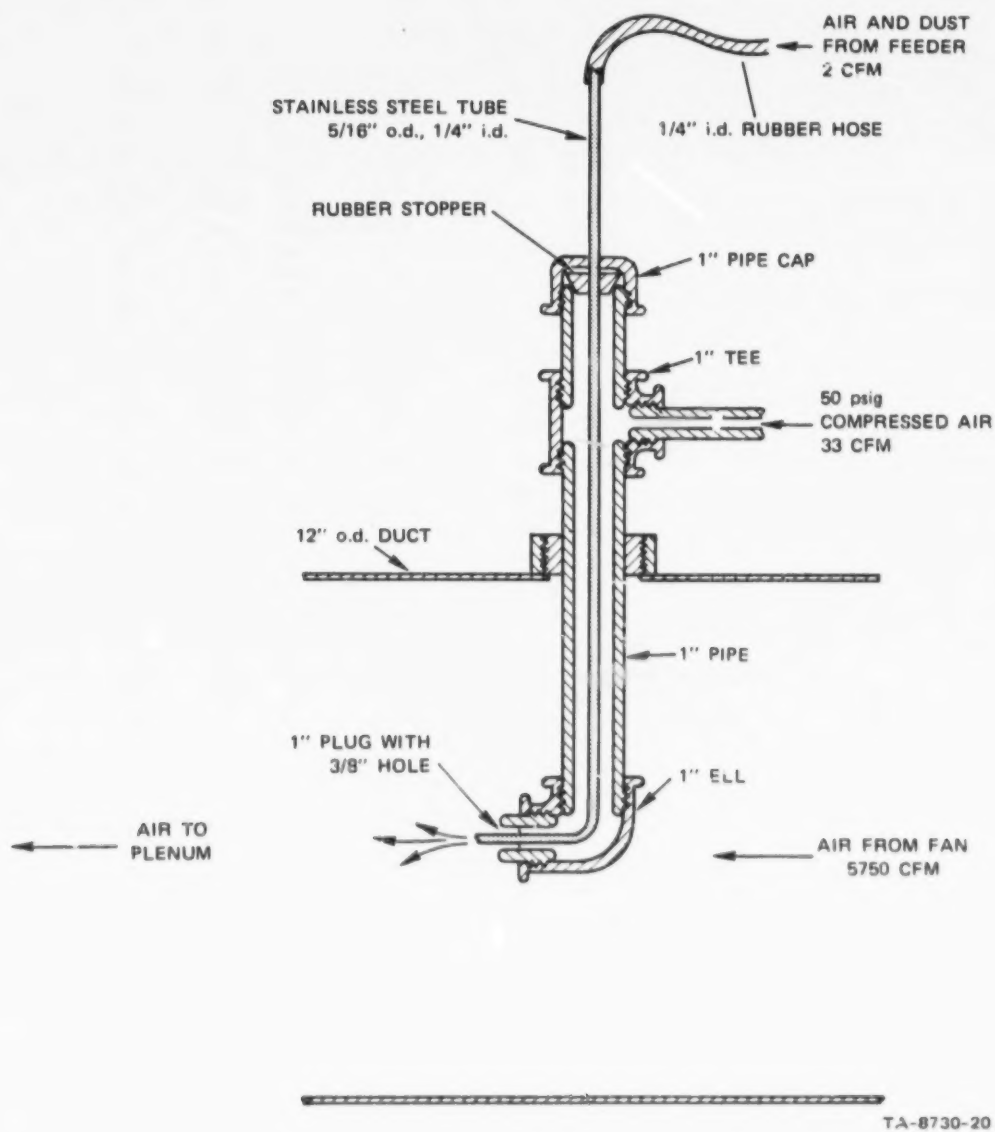


FIGURE A-3 DUST DISPERSER DETAILS

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Table A-1
DUST FEEDER CALIBRATION DATA

Groove Dimensions			Data Taken									
Centerline Diameter (in.)	Depth (in.)	Width (in.)	Fly Ash Fraction	Speed Control Setting	Number Revolutions of Disk	Powder Collected (Grams)	Time (Sec.)	Disk Speed (RPM)	Feed Rate* (g/rev)	Date		
3.50	1/16	1/8	0-10 μ	15	---	32.5	4620	0.255 [†]	1.66	11/17/70		
				30	---	42.9	1980	0.808 [†]	1.61			
				40	---	40.9	1200	1.224 [†]	1.67			
				50	---	54.5	1200	1.643 [†]	1.66			
				60	---	89.2	1800	2.05 [†]	1.45			
				80	---	90.2	1200	2.81 [†]	1.61			
				100	---	86.1	900	3.58 [†]	1.60			
				200	---	70.9	600	4.20 [†]	1.69			
										Av. 1.64		
			5-10 μ	20	3	5.1	432	0.417	1.70	9/23/71		
				18	18	29.4	2882	0.374	1.63			
				40	3	5.2	152	1.183	1.73			
				18	18	29.3	911	1.183	1.63			
				100	3	4.8	57	3.16	1.60			
				18	18	28.4	327	3.30	1.58			
										Av. 1.63		
			2.5-5 μ	20	18	26.9	2844	0.379	1.50	9/23/71		
				40	18	26.3	913	1.183	1.46			
				100	18	25.2	317	3.40	1.40			
			0-2.5 μ	20	18	18.1	2840	0.380	1.005	9/23/71		
				40	18	16.1	943	1.145	0.895			
				100	18	15.3	320	3.37	0.850			
			3.50	1/8	1/2	0-10 μ	20	1	12.3	157	0.382	12.3
20	3	36.9					486	0.370	12.3			
40	3	36.1					154	1.17	12.0			
100	3	35.8					54	3.34	11.9			
5-10 μ	20	3				39.3	490	0.367	13.1	2/26/71		
	40	3				36.1	155	1.16	12.0			
	100	3				33.1	57	3.16	11.0			
2.5-5 μ	20	3				34.7	492	0.366	11.6	2/18/71		
	40	3				34.5	156	1.15	11.5			
	100	3				34.1	54	3.33	11.4			
							Av. 11.5					
0-2.5 μ	20	3				22.7	480	0.375	7.58	2/26/71		
	40	3				23.2	160	1.13	7.73			
	100	3				22.5	53	3.40	7.50			
							Av. 7.60					

Table A-2

EFFECT OF COMPRESSED AIR PRESSURE ON DUST DISPERSION*

<u>Speed Control Setting</u>	<u>Compressed Air Pressure (psig)</u>	<u>Transmissometer Reading at Equilibrium (percent)</u>
100	50	38
	40	38
	30	41
	20	55
	10	63
40	50	72
	40	71
	30	71
	20	77
	10	90
20	10	92

* General conditions: Fraction dust fed: 2.5 to 5 μ
Disk groove: 1/8 in. x 1/2 in.

Table A-3

SUMMARY OF DUST COLLECTED INSIDE AEROSOL DUCTWORK AND TUNNEL*

	Weight Collected	
	g [g/sq ft]	
Transition Section	41	[2.5]
Plenum Chamber	311	[5.8]
Central Section (6 ft long)	74	[7.4]
3 ft NE and adjacent to Central Section	30	[6.0]
3 ft SW and adjacent to Central Section	46	[9.2]
10 ft balance of NE section	89	[5.3]
10 ft balance of SW section	72	[4.3]
Wind Tunnel	155	[3.1]
Central distributor (3 ft long)	(20)†	[4]
10 1/2 ft NE and adjacent to Central distributor	67	[3.8]
10 1/2 ft SW and adjacent to Central distributor	51	[2.9]
3 ft inside of NE aerosol curtain	6	[1.2]
3 ft inside of SW aerosol curtain	11	[2.2]
Total Collected‡	507 = 1.1 lb	

* Substantially no deposit in duct upstream of transition section; upstream 3 ft of transition section also almost free of deposit. Weights given above were swept up from bottom with a vacuum cleaner. The sides contained a coating of dust but the quantity of dust was negligible (< 20%) compared with deposit on bottom. All weights in grams. Values in brackets are approximately g/sq ft.

† Not measured or collected but estimated by noting depth and nature of deposit relative to other measured sections.

‡ Total dust fed into system prior to these measurements was approximately as follows:

Dust Fraction	Amount Fed (lb)
0-2.5 μ	9.0
2.5-5 μ	7.7
5-10 μ	15.1
0-10 μ	9.2
Total	41.0

Appendix B

FLY ASH PREPARATION AND PROPERTIES

Source

The raw fly ash used in this project was supplied by Diamond Aggregate and Fly Ash Company (501 Eleventh Avenue South, Minneapolis, Minn. 55415) to the Donaldson Company, Inc. (1400 West 9th Street, Minneapolis, Minn. 55431) for further treatment. Diamond Aggregate had this material in storage, but had originally obtained it from Northern States Power Company's Blackdog Power Plant in Minneapolis. It represents combustion of Southern Illinois bituminous coal during January 1969. The Blackdog power plant, built in 1954, has 4 boilers and 4 stacks and is equipped with electrostatic precipitators. It has an output of 475 megawatts when all four boilers are in use. Loading in the winter time is about 65%. It is the 4th largest power plant in the area and the only one from which fly ash is readily available. The plant generates approximately 50,000 tons of fly ash per year.

Treatment

The raw fly ash was delivered to the Donaldson Company, Inc. (later designated DCI) for size classification in their proprietary centrifugal air classifier. This classifier was originally developed for Donaldson by SRI. Its unique features are the provisions for achieving dust dispersion, which is normally a limiting factor in achieving sharp size classification in the range below 10 μ . It was also developed to be capable of production capacities corresponding to powder feed rates up to 50 lb/hr.

Prior to classification, approximately 1000 lb of the fly ash were screened through a Tyler 8-mesh sieve to remove traces of paper, gravel, and other superfluous debris. The screened material was then passed successively through the classifier at settings designed to give various splits. The complete flowsheets for all classification runs are given in Figure B-1 together with resultant material balances.

The first lot was successively classified at cut sizes of 10, 2.5, and 5μ to yield the fractions indicated. A second lot was then classified at 10μ to yield a 0 to 10μ fraction. The 0 to 10μ fraction obtained for the first lot has been designated as 0 to 10μ (F) to distinguish it from the corresponding fraction obtained from the second lot. All the 0 to 10μ (F) material was used up for the successive classifications. The 0 to 10μ and the 0 to 10μ (F) fraction should have been nominally identical. There was, however, a slight difference in the operating conditions at which each was obtained with a corresponding slight difference in results, the 0 to 10μ fraction being cut at a slightly finer size than the 0 to 10μ (F) fraction.

In the classification system, the fines are collected in a cyclone. Any fines escaping the cyclone are collected in a filter. Because of the small amount of material involved, all filter fractions from all the classification runs were combined into a single fraction called "Super-fines," as indicated in Figure B-1. Although a total of 9.0 lb were collected in the filter as determined by direct weighing, only approximately 5 lb were physically recovered, the remainder being either left in the pores of the filter medium or lost during shaking of the filter to remove the dust deposit.

Properties

Particle size analyses were conducted by DCI using the Fisher Sub-Sieve Sizer, the Coulter Counter, and MSA-Whitby sedimentation techniques. The Fisher analysis was checked by Stanford Research Institute (SRI). The results of all analyses are summarized in Table B-1 and plotted in Figures B-2 and B-3. The mass media diameters given in Table B-1 were obtained from the 50% intercept of the curves shown in Figures B-2 and B-3. The sp gr of material in all fractions was assumed to be 2.46 for purposes of any calculations for interpretation of results of size analyses. It is likely that the sp gr will vary with the fractions although such measurements were not made during the study. A summary of the mean sizes derived from each method is given in Table B-2.

The data shown in Figures B-2 and B-3 can be approximated by a log-probability relationship. This was done by visually fitting the best straight line to the data of Figures B-2 and B-3 giving emphasis to the data in the 10- to 90-cumulative percent range and ignoring those outside of that range. These straight lines can then be described in terms of two parameters, a mass media diameter and a standard geometric deviation. These parameters are summarized for each dust fraction in Table B-3 together with corresponding calculated* values of other mean sizes (D_{32} and D_{m0}). Since the Fisher Sub-Sieve Sizer supposedly measures D_{32} values, the Fisher data have also been included in Table B-3 for comparison.

As might be expected all methods yield different particle size results since different particle properties are assessed by each method.

* The calculation methods are described by C. E. Lapple in "Particle-Size Analysis and Analyzers," Chem. Eng., 75 (11), 149-156, (May 20, 1968)

Table B-4 lists suggested effective values in terms of optical properties for each of the dusts employed in this study. These were derived as a matter of personal judgment assuming that: (1) the optical effects are most nearly related to D_{32} values; (2) the Fisher Sub-Sieve Sizer value comes closest to measuring D_{32} ; and (3) the distribution (in terms of standard geometric deviation) can be taken from the MSA and Coulter Counter data. Because of these brash assumptions, these effective values cannot be considered as having any great precision but they are as good as can be obtained in the present state of the art. The values of D_{m3} and D_{m0} given in Table B-4 have been calculated from the quoted value of D_{32} and σ by standard methods.*

The fractions were examined at SRI both in the optical microscope and in the scanning electron microscope. Photomicrographs of the various fractions are shown in Figures B-4, B-5, B-6, and B-7.

No chemical analyses were made on the fly ash used in the project. However, Diamond Aggregate and Fly Ash Company in 1966 supplied the data given in Table B-5 on fly ash samples from two other Northern States Power generating plants in the Minneapolis/St. Paul area. These analyses are averages from samples taken over more than twelve months of operation.

The superfine, 0-2.5 μ , 2.5-5 μ , and 5-10 μ fractions were prepared by classifying the 0-10 μ fraction. The size distribution of the 0-10 μ fraction can be calculated from the mass balance data of Figure B-1 and the Fisher diameter of each of the composite fractions, assuming that the Fisher diameter is a reasonably good measure of the mass median diameter of each of the composite fractions. Since the standard geometric deviation of these composite fractions is of the order of 1.5, it can be shown

* Ibid

from the methods described by Lapple* that the mass median diameter will be only about 9% greater than the $\bar{D}_{32}$ diameter (which is presumably the Fisher diameter). On this basis the 0-10 μ fraction would have the following size distribution:

Particle Diameter microns	Cum. Wt. % Finer Than
$6.5 \times 1.09 = 7.1$	67.8
$3.1 \times 1.09 = 3.4$	22.4
$1.7 \times 1.09 = 1.85$	5.5
$0.77 \times 1.09 = 0.84$	0.8

A plot of these data yields a mass median diameter of 3.4 microns.

It should also be noted that the Fisher size of the 0-10 μ fraction calculated from the measured Fisher sizes of the component fractions is 4.0 μ . This checks exactly with the measured Fisher size for the 0-10 μ fraction. In all the above calculations the SRI measurements of Fisher size shown in Table B-1 have been used.

*Ibid



* Loss obtained by difference between feed weight and total weight of recovered fractions.

† Mechanical failure occurred early in run and both coarse and fine fractions obtained prior to failure were discarded.

‡ Rates given are powder feed rates to classifier.

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FIGURE B-1 FLOWSHEET FOR CLASSIFICATION PROCESSES

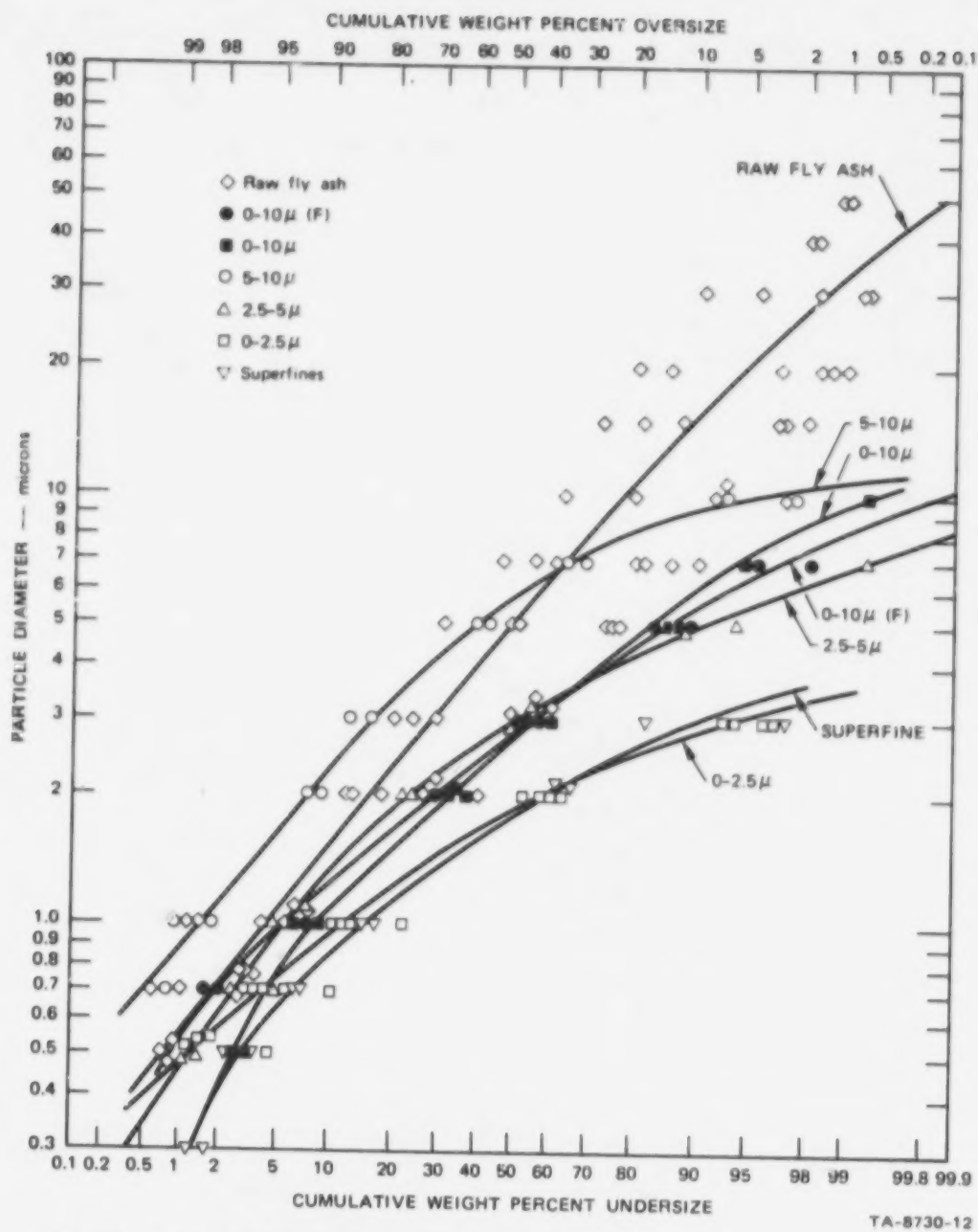


FIGURE B-2 MSA-WHITBY PARTICLE SIZE ANALYSES OF BLACKDOG FLY ASH

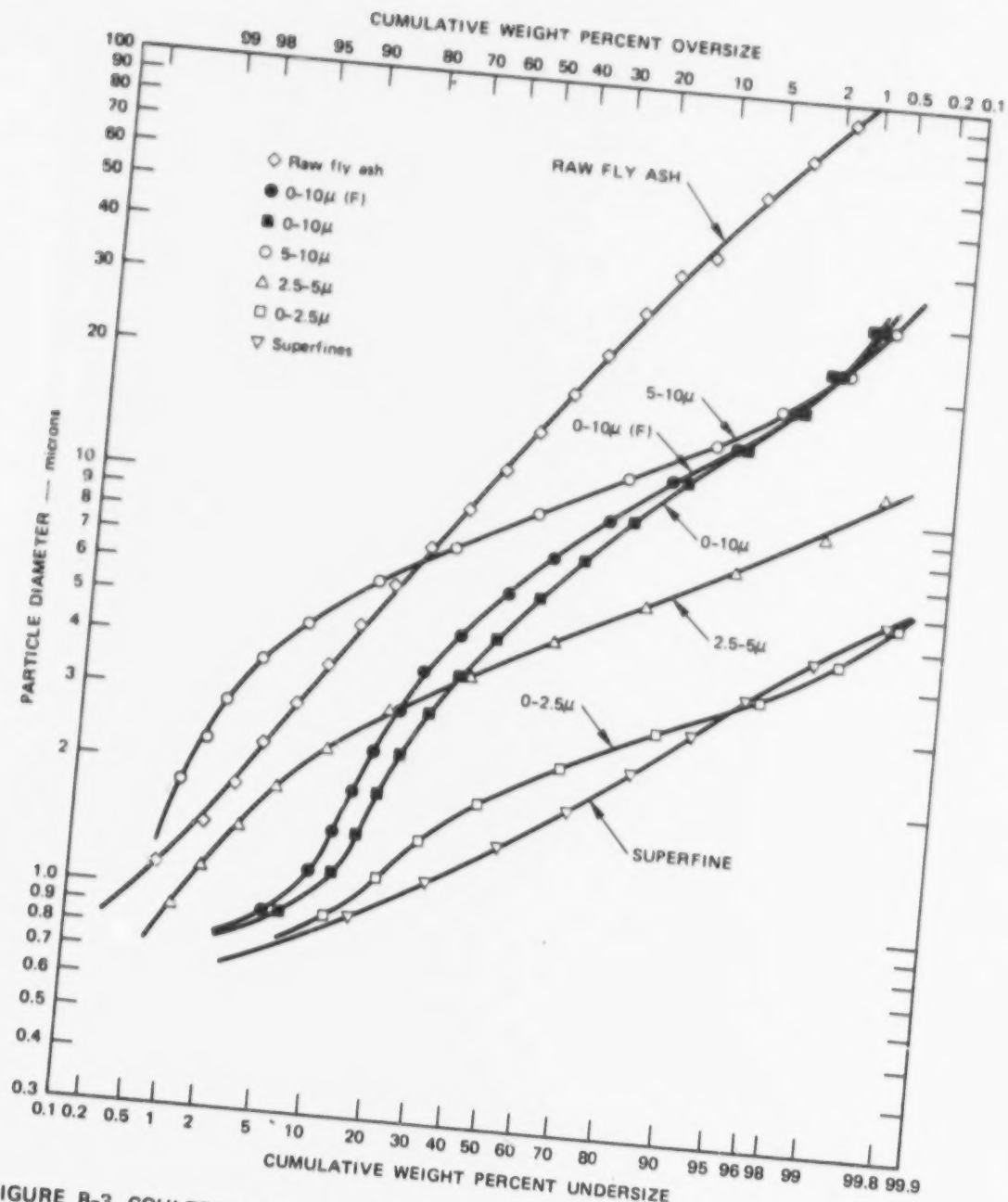
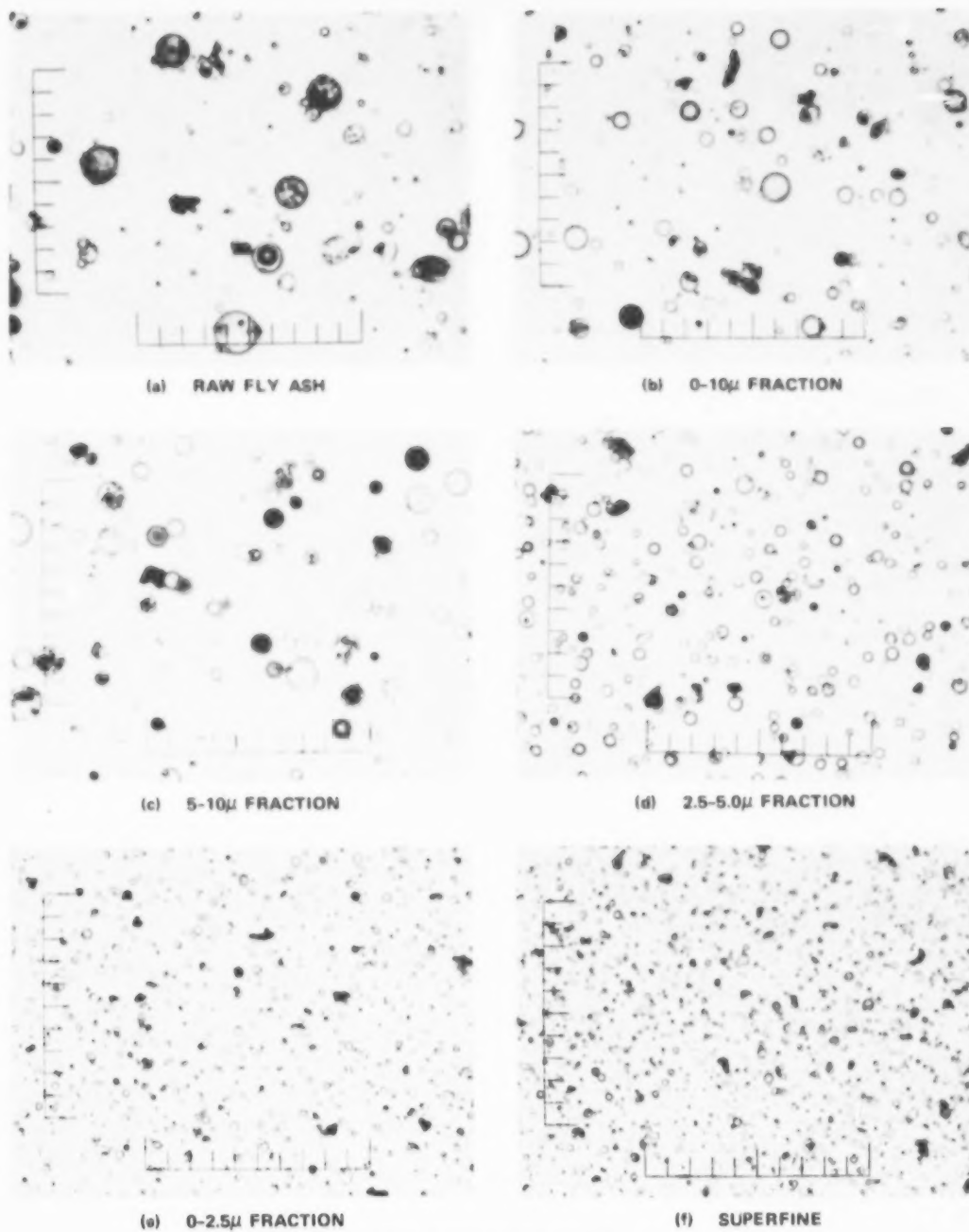


FIGURE B-3 COULTER COUNTER PARTICLE SIZE ANALYSES OF BLACKDOG FLY ASH

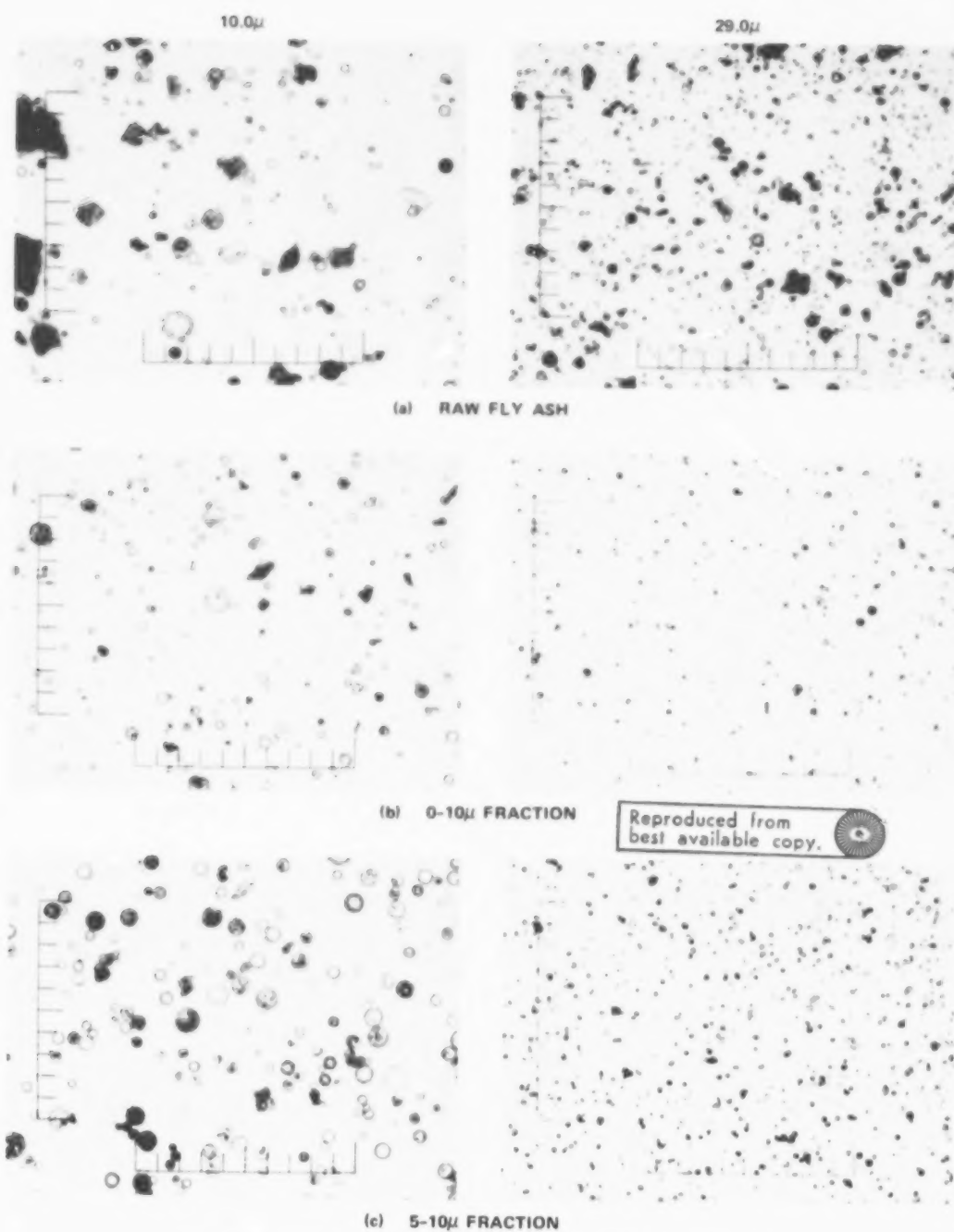
TA-8730-13



SMALLEST DIVISION ON SCALE = 6.7 μ

TA-8730-14

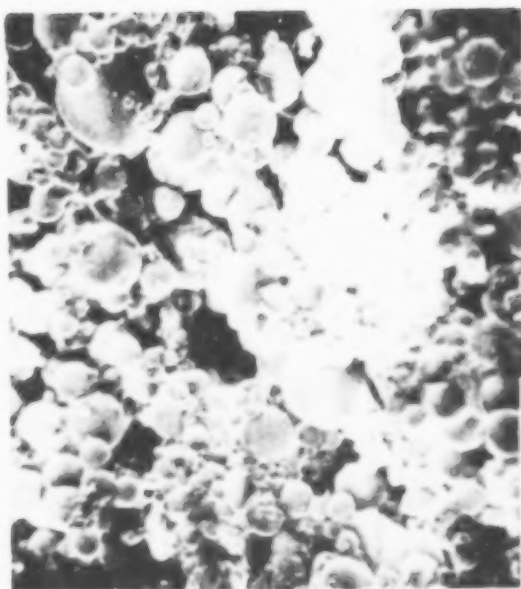
FIGURE B-4 PHOTOMICROGRAPHS OF BLACKDOG FLY ASH



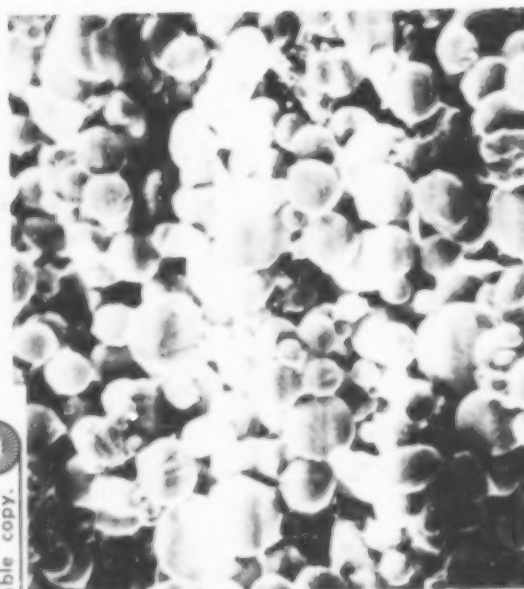
NUMBER ABOVE EACH COLUMN GIVES MAGNITUDE OF SMALLEST
SCALE DIVISION IN EACH PHOTOGRAPH IN THAT COLUMN

TA 3730-15

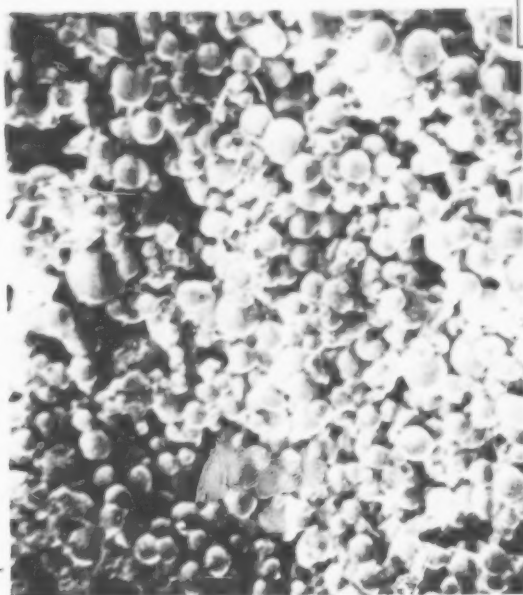
FIGURE B-5 ADDITIONAL PHOTOMICROGRAPHS OF BLACKDOG FLY ASH AT LOWER
MAGNIFICATION



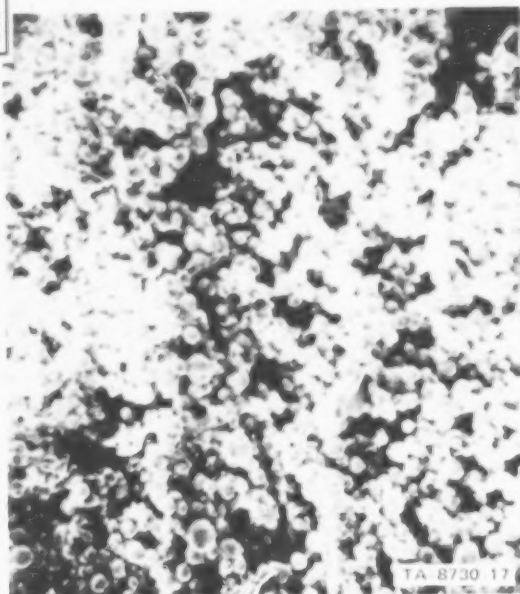
(a) 0-10 μ FRACTION



(b) 5-10 μ FRACTION



(c) 2.5-5 μ FRACTION



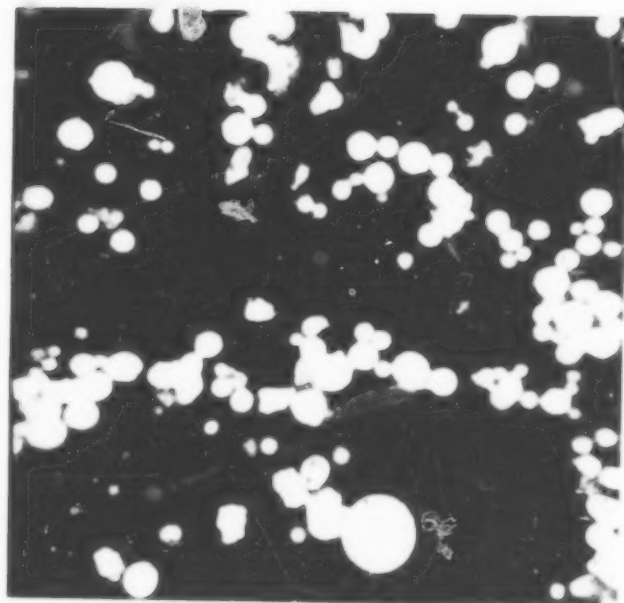
(d) 0-2.5 μ FRACTION



FIGURE B-6 SCANNING ELECTRON MICROGRAPHS OF BLACKDOG FLY ASH



(a) RUN 74A (0.25- μ Fly Ash)



(b) RUN 80A (2.5-5- μ Fly Ash)



1 μ 2 μ 3 μ 5 μ

NOTE: Filter paper G.E. "Nucleopore", 1 μ pore size.

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FIGURE B-7 SCANNING ELECTRON MICROGRAPHS OF FLY ASH DEPOSITS ON SAMPLING FILTER PAPERS

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Table B-2
SUMMARY OF MEAN PARTICLE DIAMETERS OF BLACKING FLY ASH

Size Analysis Method	Fraction						
	Raw Fly Ash	0-10 μ (F)	0-10 μ	5-10 μ	2.5-5 μ	0-2.5 μ	Superfine
Fisher Subsieve Sizer, diameter corrected for slip-flow, μ DCI SRI	8.4	4.5	4.4	7.7	3.9	2.1	0.64
	8.11	4.00*	3.95	6.47	3.10	1.70	0.77
Coulter Counter, mass median diameter, μ DCI	13.7	6.2	5.0	8.8	4.1	1.93	1.43
	5.0	2.75	2.70	5.7	2.97	1.85	1.77
MSA-Whitby Sedimentation, mass median diameter, μ DCI							

* Calculated from analyses of component fractions.

Table B-3

LOG-PROBABILITY APPROXIMATIONS TO
SIZE DISTRIBUTION OF EACH FRACTION OF
BLACKDOG FLY ASH

Fraction	Size Analysis Method	Standard Geometric Deviation σ	Diameter, micron		
			Mass [†] Median	Sauter [‡]	Number [‡] Median
			D_{m3}	D_{32}	D_{m0}
Raw Fly Ash	CC	2.74	13.5	8.12	0.64
	MSA	2.50	5.0	3.28	0.40
	F	-	-	8.1	-
0-10 μ (F)	CC	2.41	5.80	3.94	0.57
	MSA	1.78	2.75	2.33	1.01
	F	-	-	4.0	-
0-10 μ	CC	2.48	4.75	3.13	0.40
	MSA	1.93	2.70	2.17	0.74
	F	-	-	4.0	-
5-10 μ	CC	1.51	8.60	7.90	5.17
	MSA	1.70	5.40	4.74	2.32
	F	-	-	6.5	-
2.5-5 μ	CC	1.50	4.00	3.68	2.44
	MSA	1.62	2.90	2.58	1.44
	F	-	-	3.1	-
0-2.5 μ	CC	1.52	1.85	1.70	1.09
	MSA	1.46	1.80	1.67	1.17
	F	-	-	1.70	-
Superfine	CC	1.64	1.46	1.29	0.70
	MSA	1.61	1.80	1.61	0.91
	F	-	-	0.77	-

* CC = Coulter Counter; MSA = MSA-Whitby Sedimentation; F = Fisher Sub-Sieve Sizer

† Obtained from best straight line through data in log-probability paper in 10 to 90 cumulative percent range

‡ Calculated from σ and D_{m3}

Table B-4

RECOMMENDED "AVERAGE" SIZE DISTRIBUTION
FOR EACH FRACTION USED IN STUDY

Fraction	Standard Geometric Deviation	Diameter, microns		
		Mass Median D_{m3}	Sauter D_{32}	Number Median D_{n0}
0-10 μ	2.2	5.45	4.0	0.85
5-10 μ	1.5	7.06	6.5	4.31
2.5-5 μ	1.5	3.36	3.1	2.06
0-2.5 μ	1.5	1.85	1.7	1.13

Table B-5

TYPICAL FLY ASH ANALYSES

Generating Plant (Station)	High Bridge	Riverside
Location	St. Paul	Minneapolis
Physical Analyses		
Specific gravity	2.36	2.50
Sieve analysis		
% passing 200 mesh	92	97
% passing 325 mesh	81	91
Blaine, surface area, sq cm/g	3110	3491
equiv diam, μ	8.15	6.87
Hygroscopic moisture, %	0.02	0.11
Chemical Analysis, %		
SiO ₂	49.6	47.6
Al ₂ O ₃	18.0	16.9
Fe ₂ O ₃	18.5	21.9
CaO	4.8	4.3
MgO	0.8	0.8
SO ₃	1.3	1.0
Ignition Loss, %	3.4	3.3

Appendix C

DUST CONCENTRATION CONTROL AND MEASUREMENT

Dust Concentration Control

The dust concentration in the system was controlled by establishing known rates at which both air and dust were admitted to the chamber system. The dust feed rate was controlled by the size of groove in and the rotational speed of the disk used in the feeder described in Appendix A. The total air flow rate was essentially constant throughout all the tests, a given fan being operated at a fixed speed on a system of fixed geometry. The air rate was measured and monitored as described in Appendix A.

Calculation of Dust Concentration

Since both dust and air were admitted to the aerosol chamber at fixed and known rates, the dust concentration existing in the sighting tunnel can be calculated if it is assumed that there is no deposition or accumulation of dust within the chamber. This calculated concentration (termed "feeder concentration") is obtained by dividing the dust feed rate by the total air rate. The dust feed rate is established from the feeder calibration data given in Appendix A and the feeder disk rotational speed. Although the disk speed was determined by the speed control setting, some small speed differences were noted at a given setting presumably because of differences in frictional resistance in the drive. For this reason the disk speed was measured in each run by a microswitch that was activated momentarily once every revolution of the disk. This generated a mark on the transmissometer strip-chart recorder from which the actual disk speed could be calculated for each run.

Recognizing at the start of the program that dust deposition in the aerosol chamber could be a problem, the dust sizes and air rates were chosen so as to minimize this difficulty. Although it was not feasible to eliminate entirely deposition with any reasonable system, it was expected that such problems should be minor, reflecting a change in dust concentration of less than 10%. To achieve this, however, it was also necessary to disperse completely the dusts used. The compressed-air disperser described in Appendix A was designed to provide as good a dispersion as possible with known technology.

Concentration Measurements Techniques

To provide a separate check on concentration, separate measurements of concentration were made by sampling the dust-laden stream from the sighting tunnel. During the course of the program three different sampling devices were used.

In the beginning of the program a simple probe inserted into the aerosol chamber at right angles to the nominal flow was used as shown in Figure C-1. This arrangement was designated as the "T" arrangement. Although it is customary to use isokinetic sampling when dealing with particulates to avoid sampling bias caused by particle inertia, this would have been very difficult to achieve because of the low air velocities in the chamber. It was also felt that with most of the dusts the inertial sampling bias should not be too severe and hence the simple form of sampling probe was used.

Air was pulled through the sampling train at a constant and metered rate by connecting the sampling system to a high vacuum line through a critical flow orifice (approximately 0.025-in. diameter). This orifice was calibrated against a gas prover. Sampling rate was held constant at a predetermined value by maintaining a given upstream pressure on the

orifice by means of a valve located upstream of the orifice. The pressure downstream of the orifice was always recorded to be certain that critical flow was being realized. A sampling rate of 2.55 l/min was used. The filter medium was a 1-in.-diameter General Electric "Nuclepore" medium of 1- μ pore size. One side of this medium is smooth and the other is matte. The dust was allowed to deposit on the matte side. This filter medium was used because of its light weight (5 to 6 mg) and low moisture retention (less than 0.01 mg, as established in another study). Before and after sampling, the filter disks were stored in an aluminum cup that in turn was placed in a closed plastic box. The aluminum cup was used to mitigate the possible repulsive forces arising from electrostatic charges on the filter medium.

The second sampling technique used the Delrin filter holders shown in Figure C-2. These filter holders were placed over the 1-in. sampling ports or located directly in the aerosol stream. Two such units were always operated at the same time (although not at the same sampling location) and air was drawn through each at a rate of 2.55 l/min by a separate critical-flow orifice similar to that used for the first sampling technique. The same "Nuclepore" filter medium was also used. The filter holders were used in four orientations: (1) pressed over the 1-in. sampling ports with the filter medium parallel to the chamber walls; (2) vertical, facing into the nominal direction of air flow, so that the filter face is normal to the nominal air flow; (3) horizontal with the filter medium facing upward and parallel to the air flow; and (4) horizontal with the filter medium facing downward and parallel to the nominal air flow. As will be noted from Figure C-2, there were two types of holders: (1) an "open" filter in which essentially the entire filter medium (13/16-in. diameter free area) was exposed directly to the air stream; and (2) a "closed" filter in which the air must pass through a nominal

5/16-in.-diameter hole before arriving at the filter medium. It should be noted that the air velocity in the sighting tunnel was nominally 4.4 ft/sec (133 cm/sec) whereas, at a sampling rate of 2.55 l/min, it was almost the same [2.8 ft/sec (86 cm/sec)] in the inlet opening of the closed filter. In the "open" filter with an inlet opening of 13/16 in., the velocity was 0.42 ft/sec (13 cm/sec).

A few runs were made with the sampling arrangement shown in Figure C-3. This entire unit was inserted into the sighting tunnel with the nozzle mouth facing into the air stream. Large volumes of air were thus sampled by a vacuum cleaner, and dust was collected in a paper vacuum cleaner bag in relatively large quantity. The air flow was measured by the inlet nozzle to the system. The velocity at the mouth of the nozzle (2-in. diameter) was of the order of 15 ft/sec (460 cm/sec). The air flow in this case was determined largely by the resistance of the bag. Although the air flow was reasonably constant during a run, it varied markedly with the way in which the bag was inserted in the holder because of the close clearance between wall and bag.

With all the sampling arrangements, samples were taken at various locations, identified in Figure C-4.

Sampling Results

The details of data taken during the series of samplings with sampling arrangement "T" are given in Table C-1. In these runs the sampling arrangement was held constant and samples were taken at a variety of locations with three of the dust fractions. It was during the course of these measurements that the Mark V lidar shots were made.

Since it was obvious that there were problems in obtaining a correct sample, at a later date a second series of runs were made in which the feed rate was held essentially constant (at the same speed control setting), and the type of sampler and the sampler orientation and location were varied with each of the dusts. These results are given in Table C-2.

To give a simple indication of the sampling runs, the data were reported as a ratio of the concentration calculated from the feeder speed to that measured on the sampling filter. These ratios are summarized in Table C-3 for the data of Table C-1 and in Table C-4 for the data of Table C-2.

With the "T" sampling arrangement, the data of Table C-3 shows a distinct trend of the concentration ratio with dust fraction. Although there is some trend with sample location, this is overshadowed by the effect of dust fraction. In the second series of runs (Table C-4), the concentration ratio also shows a distinct trend with dust fraction although some effect of sampling arrangement is demonstrated. In both cases this is best illustrated by the following arithmetic averages of all concentration ratios measured for each dust fraction, leaving out concentration ratio values that are obviously grossly in error.

AVERAGE CONCENTRATION RATIO (Feeder/Filter)				
Dust Fraction	For "T" Sampling Arrangement (Table C-3)	For Second Series of Runs (Table C-4)		
		All Data	Data for CH _u Arrangement Only	Data for OH _u Arrangement Only
0 - 2.5 μ	1.28	0.98	1.02	0.94
2.5 - 5 μ	2.08	1.53	1.65	1.42
5 - 10 μ	--	1.75	2.39	1.48
0 - 10 μ	3.61	1.83	2.10	1.66

It is apparent that the concentration ratio is essentially greater than unity and increases with increasing dust particle size. A concentration ratio greater than unity means that the concentration measured with the filter is less than would be calculated from the dust feed rate.

Uniformity of Aerosol Concentration

The best indication of the overall degree of uniformity of the aerosol concentration in the chamber is through the transmissometer strip-chart readout. Figure C-5 shows typical recordings obtained for the various dusts at a variety of dust concentration levels. The run numbers correspond to those cited in Tables C-1 and C-2. Figure C-5 gives the nominal transmissometer readout as a function of time. The range in the transmissometer scale is nominally 20% to 100%, with 100% being at the left. The chart was calibrated during each group of runs since there was some drift in calibration and the readout was not quite linear. It is for this reason that the transmissometer scale is termed nominal. The 100% level is almost correct on an absolute basis but the indicated 20% reading may have been as high as 25% on an absolute basis. The strip chart was operated at its lowest speed of 1 mm/sec in all cases, with the smallest time-scale divisions being 5 mm (hence, 5 seconds) apart.

From Beer's law, the aerosol mass concentration is related to transmission by

$$w_p = K \ln(1/T)$$

where

w_p = mass concentration, mg/m^3

T = fractional light transmission, dimensionless

K = proportionality factor, mg/m^3

By differentiation

$$\left[\frac{\frac{\Delta w}{w}}{\frac{p}{p}} \right] = - \left[\frac{\Delta T}{T \ln(1/T)} \right]$$

Here $\frac{\Delta w}{w} \frac{p}{p}$ is the fractional change in aerosol concentration with a change in transmission, ΔT . For values of T greater than 70%, a close approximation is:

$$\left[\frac{\frac{\Delta w}{w}}{\frac{p}{p}} \right] = - \left[\frac{\Delta T}{1 - T} \right] = \left[\frac{\Delta(1 - T)}{(1 - T)} \right]$$

This says that for transmissions greater than 70%, the fractional change in aerosol concentrations should be proportional to the fractional change in opacity, $(1 - T)$. In the region of T between 10 and 70% a reasonable approximation is

$$\frac{\frac{\Delta w}{w}}{\frac{p}{p}} = 3 \Delta T$$

From the above relationships, the variations in concentration with time can be estimated from the variation in transmission with time shown in Figure C-5. It will be noted that for the coarsest dust fraction, 5 - 10 μ , which is relatively free flowing, the concentration variation during a run is less than $\pm 5\%$. For the finest and least free-flowing dust, 0 - 2.5 μ , the concentration variation is only some $\pm 15\%$.

The traces in Figure C-5 indicate occasional spurts in concentration, especially with the finest dust. These were demonstrated to result from tapping or vibration of the dust feed line to the aerosol disperser; either would momentarily dislodge a buildup of dust in this line. This could also

be deduced from the fact that such a spurt is always in the direction of increased concentration and the fact that a time of about 6 seconds (twice the nominal aerosol chamber retention time) is required for this perturbation in concentration essentially to disappear.

It may, therefore, be concluded that the aerosol concentration in the tunnel remained uniform to better than $\pm 15\%$ throughout a run except for an occasional short-lived increase.

Sources of Sampling Error

The following are possible sources of sampling error:

- (1) Error in concentration of coarse particles because of failure to achieve isokinetic sampling conditions. With sampling velocities higher than those of the stream being sampled, a low apparent concentration of coarse particles will be measured; the reverse will be true if sampling velocities are too low. The following is a summary of approximate nominal velocities under the test conditions employed:

In sighting tunnel	4.4 ft/sec (133 cm/sec)
In plenum chamber	7.3 ft/sec (223 cm/sec)
Entering open "Delrin" filter	0.42 ft/sec (13 cm/sec)
Entering closed "Delrin" filter	2.8 ft/sec (86 cm/sec)
Entering "T" arrangement	2.8 ft/sec (86 cm/sec)
Entering bag sampler nozzle	15 ft/sec (460 cm/sec)

The above statements assume that the sampling port points into the gas stream. If the gas stream flow direction is other than directly into the sampling port, there will be a tendency toward measuring low apparent concentrations.

- (2) Deposition in sampling lead lines. This was probably a major factor in the "T" arrangement in addition to any sampling bias and would result in the radically lower measured concentrations observed with that arrangement.

- (3) Electrostatic repulsion at the probe intake. Particles subjected to the violent impact and shearing in the compressed-air disperser can acquire electrostatic charges, the sign of which can be asymmetric. When such particles deposit on an insulated wall, an electrostatic field is set up that will tend to repel those particles bearing the predominant sign of charge. Such electrostatic effects are likely to be more pronounced with the coarser particles.
- (4) Failure to retain particles on the filter medium. This can happen because of electrostatic charges or because of mechanical action. The "Nuclepore" medium can acquire very large charges that could repel particles of similar charge and keep them from landing. Mechanical vibration or flexure in handling the filter papers could result in a loss of deposited particles. Indeed, in a few cases it was observed that particles were propelled into space when the filter paper was removed from the holder, although the magnitude of this action was not assessed quantitatively. This behavior could be caused by either electrostatic or vibrational effects. In either case, the action would be expected to be most pronounced with the coarsest particles because of the much greater tendency of fine particles to adhere to the surface. It was established that such losses did not occur during weighing. A few filters were weighed by successively removing them from and replacing them in their storage containers between weighings. The loss in dust deposit after several such manipulations was negligible (less than 5% of total dust deposit) when dealing with the 5 - 10 μ dust fraction. Such weighings, however, were made a relatively long time (hours) after sampling. Thus, strong adhesive forces may have developed and electrostatic charges may have leaked off.
- (5) Error in sample weighings. The precision of the weighing techniques was checked on numerous occasions and weighings were always reproduced within ± 0.020 mg. Such an error would be less than 10% with all but the smallest filter deposits. Although human error in weighing the clean filter papers could result, such error should be very infrequent as judged by the reproducibility achieved in reweighing of dust-laden filter papers.
- (6) Deposition of particles on the walls, roof, or floor of the tunnel. Under the test conditions such wall deposition would be most pronounced the coarser the particles. The tunnel and dust conditions were selected to minimize such effects although

such effects could not be completely eliminated. As discussed in Appendix A, measurements of wall deposits in the entire tunnel after many sampling runs indicated that such deposition was probably less than 5% of the dust feed. This conclusion, however, is not incontrovertible because of the possibility of dislodgement of wall deposits by vibration during periods between samplings. It was observed that what little dust deposit occurred on the tunnel walls was almost entirely on the horizontal surfaces. However, theoretical calculations confirm that gravity settling could account for only a small amount of deposition on the tunnel floor.

Discussion of Sampling Results

The following is a summary of the results indicated by the sampling data summarized in Tables C-1 to C-4:

- (1) The concentration ratio (feeder/filter) is close to unity for all filter arrangements and sampling locations when dealing with the finest dust fraction, 0 - 2.5 μ .
- (2) For the coarser dust fractions the concentration ratio becomes progressively larger. In the case of filter arrangement "T" the concentration ratio increases steadily with increasing particle size and becomes quite large (3.6) for the coarsest size. Although dust deposits were observed in the "T" arrangement lead lines, their magnitudes could not be established quantitatively. With the other filter arrangements the trend is the same, but there appears to be a major increase when going from the finest (0 - 2.5 μ) to the next finest (2.5 - 5 μ dust fraction). The concentration ratio then increased only slightly more for the coarsest fractions.
- (3) Although there was some trend of concentration ratio with some filter locations, the trends were somewhat erratic with the "T" arrangement. In the other arrangements the concentration ratio was more dependent on the sampling technique than on the sampling location. The open "Delrin" filter collected more dust (gave lower concentration ratio) with horizontal filter medium (OH_u , OH_d) than did the closed filter (CH_u , CH_d). For the vertical medium facing into the stream, there was little difference in concentration ratio between open and closed filter (OS, CS).

- (4) Runs in which the filters contained a heavy deposit (86, 91-94) tended to give a lower concentration ratio but the trend was not consistent.
- (5) Runs in which a double filter mat was used (87 - 90) with the deposit between the mats gave a lower concentration ratio (about 1.3 for the 5 - 10 μ fraction) than did most of the other arrangements.
- (6) With all dust fractions a significant number of samples indicated a concentration ratio of close to unity for most sampling arrangements, and sampling locations.

It is felt that the concentration determined by sampling is subject to the greatest error and that actual concentrations are close to those calculated from dust feed rates, although the actual concentrations must be somewhat lower than those so calculated. The following tabulation represents an "educated guess" on the relationship between actual and calculated concentrations.

<u>Dust Fractions</u>	<u>Concentration Ratio (Feeder/Actual)</u>
0 - 2.5 μ	1.00
2.5 - 2.5 μ	1.05
5 - 10 μ	1.10
0 - 10 μ	1.10

These values cannot be derived rigorously but are based on a considered judgment of all the above considerations.

Although particle inertia undoubtedly accounts for some of the error in the sampling measurements, it is felt that a major factor is associated with loss of dust from the filter paper due to either electrostatic effects during deposition or dust loss while removing the filter paper from the holder. The fact that the particle was reasonably spherical could be a significant factor in such accidental loss from the filter medium. This

conjecture has not been proved but is suggested by the poor reproducibility of the sampling measurements. A major consideration in this conjecture is the fact that the transmissometer readings showed excellent agreement with feeder speed settings and did not correspond to the wide variations in apparent concentration indicated by the sampling measurements for a given feeder speed setting.

Sampling with Weathermeasure Instrument

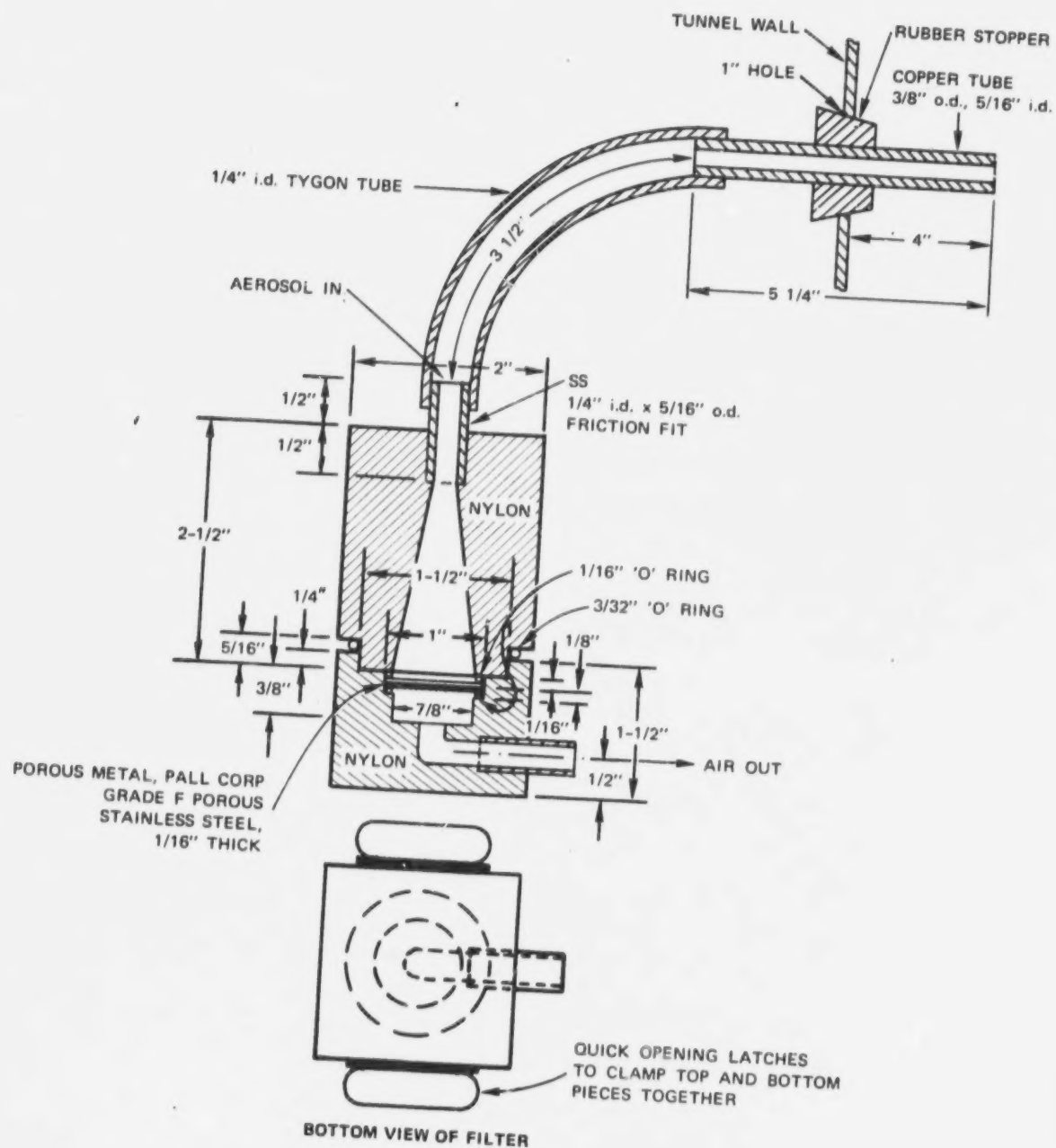
A few high-spot evaluations of the dust concentrations in the tunnel system were made by sampling through an instrument produced by Weathermeasure Corporation (Division of KMS Industries), P.O. Box 41257, Sacramento, California 95841. This instrument measures light scattered at 90° from an incident light beam. The light detector current is allowed to accumulate in a condensor that pulses whenever a given charge accumulation is reached. The count rate, which is proportional to aerosol concentration, is obtained by separately timing the number of pulses. Each such discharge is registered as a count. The instrument will also read count rate directly for rates over 100 counts/min.

In all these runs air was sampled by means of the "T" arrangement shown in Figure C-1. However, the Weathermeasure instrument was interposed between the sampling line and the filter. All the measurements were made in the course of the sampling series recorded in Table C-1. The data so obtained are summarized in Table C-5.

The Weathermeasure instrument requires calibration for each dust; hence, the results can be considered only relative. The instrument has been calibrated with $0.32\text{-}\mu$ stearic acid aerosol by the manufacturer; for this aerosol 1 count/min is reported to correspond to a particle concentration of 0.01 mg/m^3 . From the data of Table C-5, 1 count/min for $0 - 10\text{ }\mu$ fly ash would appear to correspond more nearly to a dust

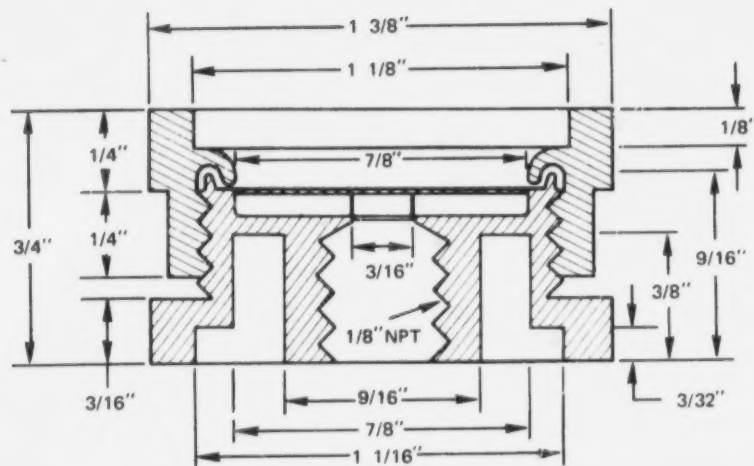
concentration of 1 mg/m^3 . With the $2.5 - 5 \mu$ fly ash, 1 count/min appears to correspond to about 0.5 mg/m^3 . Since these results are presumably also subject to the sampling errors previously discussed for sampling with the "T" arrangement, the actual instrument equivalents are probably about 1/2 those cited above (i.e., 0.5 and 0.25 mg/m^3 for the $0 - 10 \mu$ and the $2.5 - 5 \mu$ fractions, respectively).

In general, reasonable reproducibility was obtained although there was some problem with a drift in the instrument calibration setting. The manner in which the instrument was held also seemed to affect results. It was held horizontally in all the runs reported in Table C-5. The trend with sample location corresponds reasonably well to those observed in the filter sampling runs with the "T" sampling arrangement.

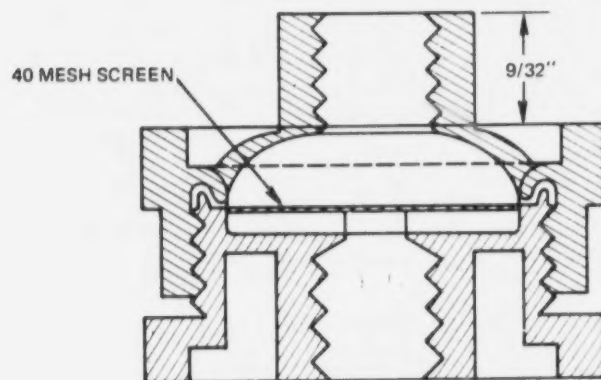


TA-8290-14R

FIGURE C-1 SAMPLING AND FILTER ARRANGEMENT



(a) OPEN GELMAN FILTER HOLDER (DELREN)



(b) CLOSED GELMAN FILTER HOLDER (DELREN)

TA-8730-22

FIGURE C-2 DELREN FILTER HOLDER

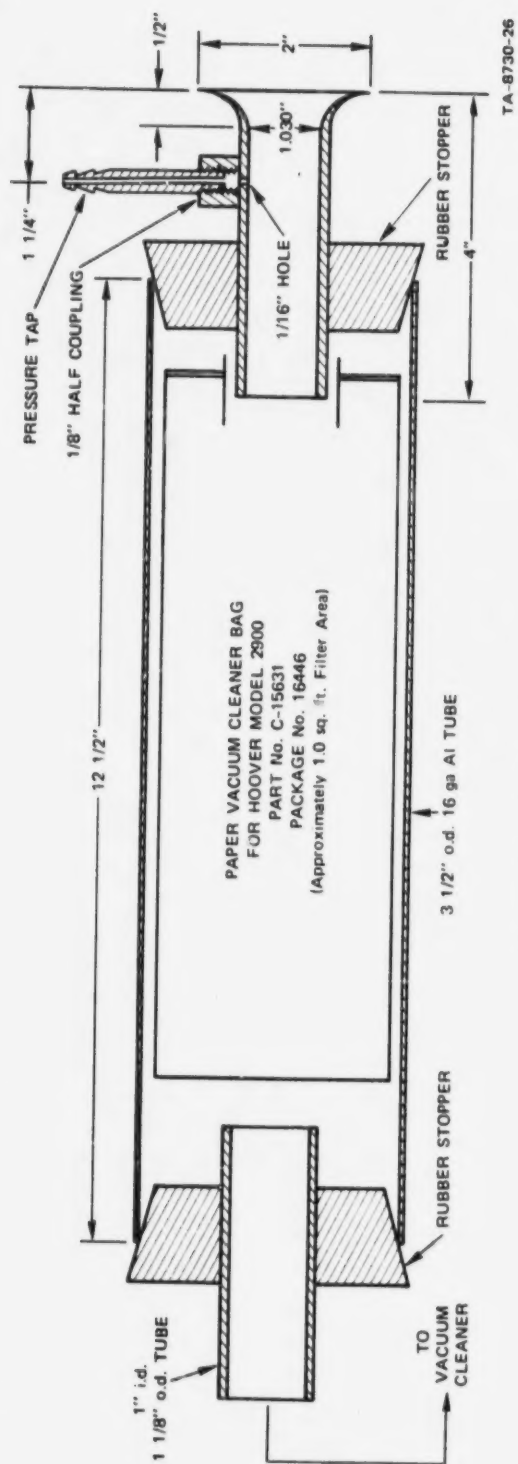
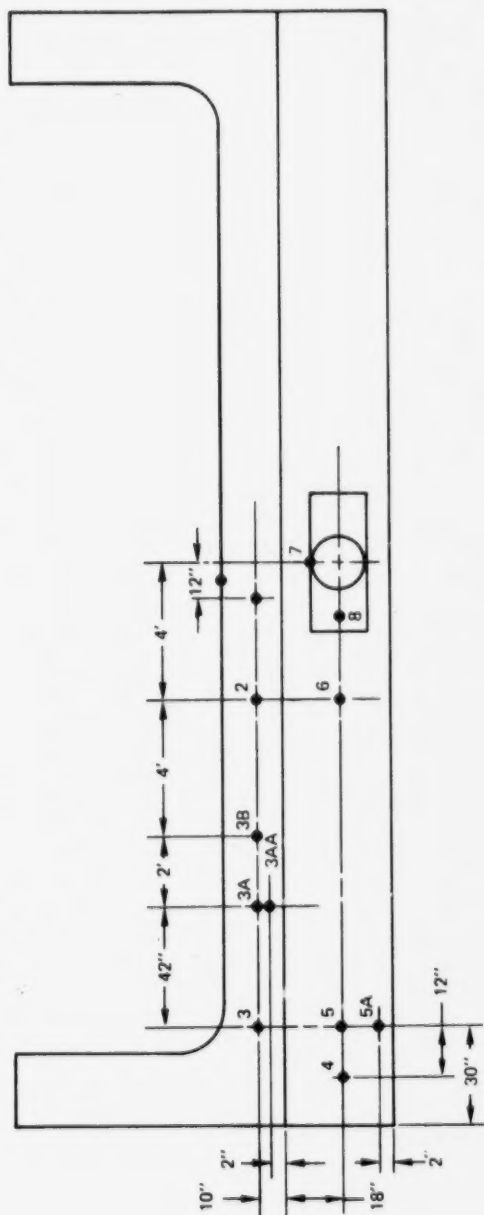
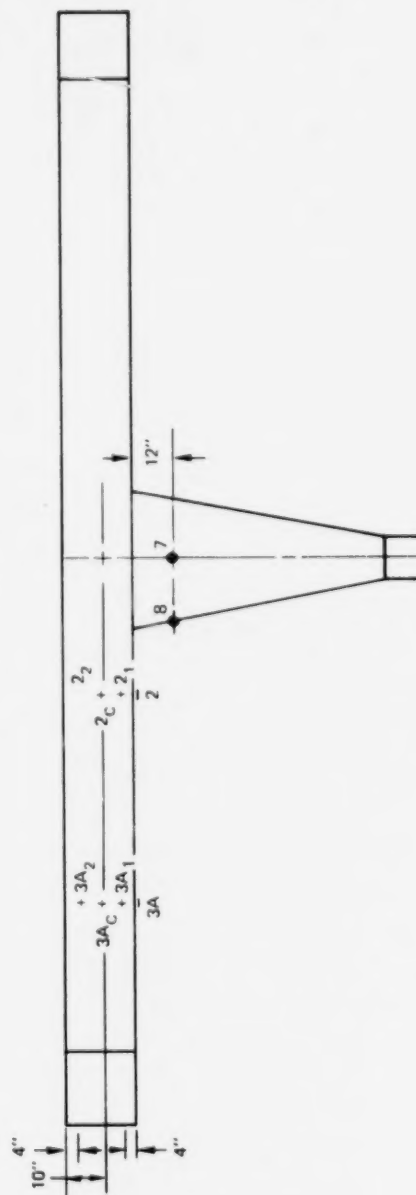


FIGURE C-3 BAG SAMPLER SYSTEM



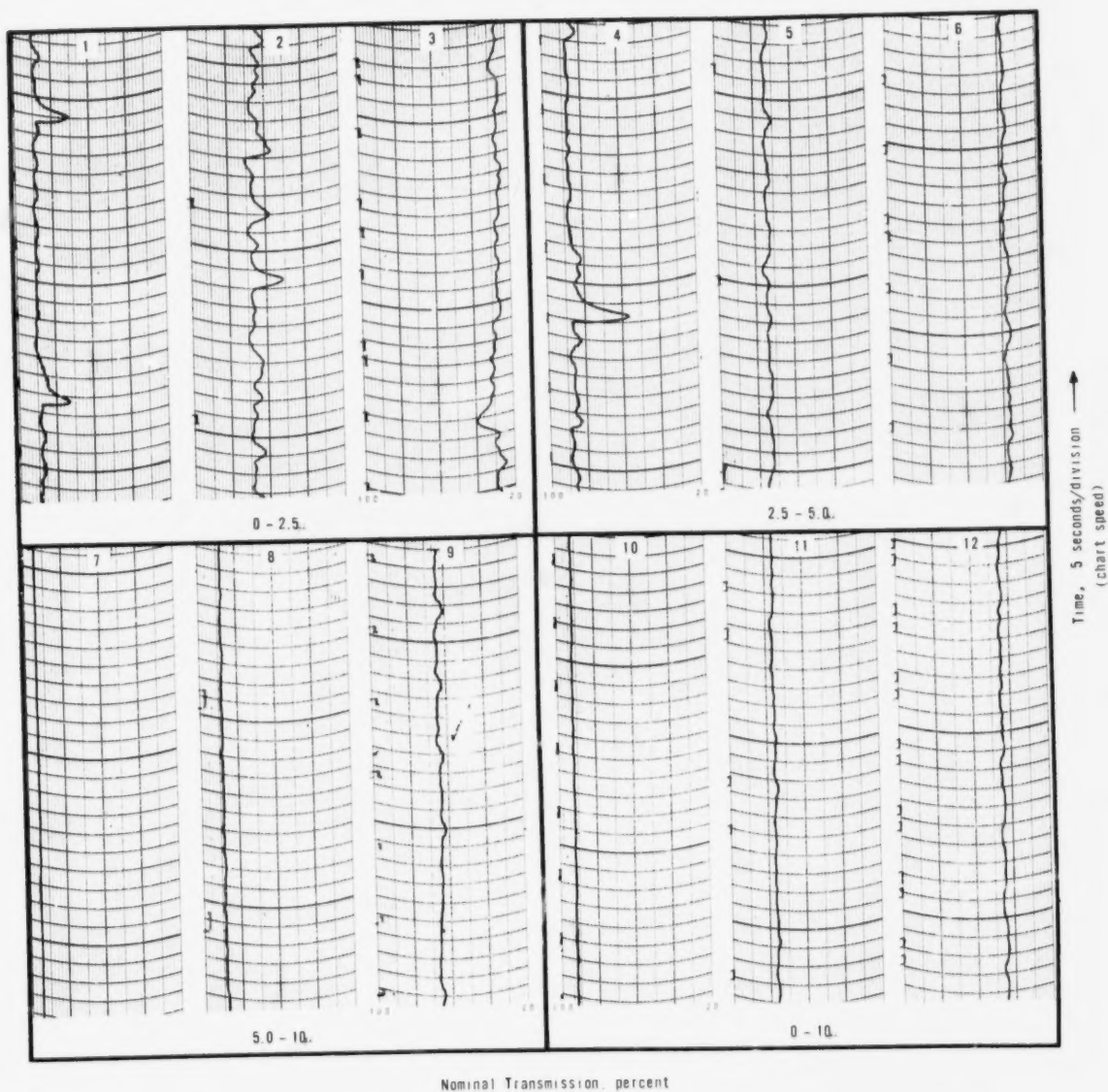
ELEVATION



PLAN VIEW

FIGURE C-4 SAMPLING LOCATIONS

TA-8730-25



DUST FRACTION	CHART NUMBER	DUST CONCENTRATION (Based on feeder) mg m ⁻³	SAMPLING RUN NUMBER	AVERAGE TRANSMISSOMETER READING DURING RUN %
0-2.5 _μ	1	16	75	86
	2	48	51	66
	3	146	48	29
2.5-5.0 _μ	4	27	79	64
	5	74	34	74
	6	222	39	42
5-10 _μ	7	32	91	95
	8	73	100	88
	9	206	101	67
0-10 _μ	10	35	66	91
	11	84	27	76
	12	241	29	48

FIGURE C-5 TYPICAL TRANSMISSOMETER STRIP CHART RECORDS OF VARIOUS DUST SIZES AND CONCENTRATIONS

Table C-1

SUMMARY OF INITIAL SERIES OF SAMPLING RUNS*

Run Number		1	2	3	4	5	6	7	8	9	10
Date		1/25/71	1/26/71	1/26/71	1/26/71	1/26/71	1/26/71	1/26/71	1/26/71	2/4/71	2/4/71
Equipment		A	A	A	A	A	A	A	A	B	B
Arrangement number											
Pressure differentials, mm											
xylene		90	92	92	92	92	92	92	94	94	94
Across nozzle		--	--	49	49	49	49	49	51	46	46
Across plenum (2-6)											
Atmospheric condition											
Temp, °C		--	--	--	--	--	--	18.5	19.0	14.5	15.0
Barometer, mm Hg		770	772	772	772	772	772	770	770	772	772
Dust type (fly ash)		0-10 _μ	0-10 _μ	0-10 _μ	0-10 _μ	0-10 _μ	0-10 _μ	0-10 _μ	0-10 _μ	0-10 _μ	0-10 _μ
Feeder											
Groove size		1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8
Variac setting		100	100	100	100	100	100	100	100	100	100
RPM		3.16	3.16	3.16	3.22	3.18	3.16	3.27	3.22	3.21	3.21
Filter											
Sampler type		T	T	T	T	T	T	T	T	T	T
Initial filter weight, mg		5.767	5.591	5.787	5.808	5.656	5.616	5.587	5.942	5.851	5.839
Dust collected, mg		0.239	0.205	0.160	0.147	0.370	0.386	0.287	0.256	0.347	0.187
Time, sec		600	600	600	600	600	600	600	600	600	600
Sampling position		2	2	6	6	3	3	5	5	8	2
Sampling rate, L/min		2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
Aerosol concentration, mg/m ³											
From feed rate		31.5	31.5	31.5	32.1	31.7	31.5	32.6	32.1	32.0	32.0
From filter sample		9.1	8.0	6.3	5.8	14.5	15.1	11.2	10.1	13.6	7.3
Ratio: feeder/filter		3.35	3.94	5.00	5.53	2.14	2.09	3.43	2.91	2.35	4.38
Average transmissometer reading		--	--	--	--	--	--	--	--	0.908	0.904
Notes											

* Common conditions: Tunnel air flow 3800 CFM including compressed air
 Sampling rate: 2.55 L/min
 Compressed air: 50 psi.

Table C-1 (Continued)

Run Number	11	12	13	14	15	16	17	18	19	20
Date	2/4/71	2/4/71	2/4/71	2/4/71	2/4/71	2/4/71	2/4/71	2/4/71	2/4/71	2/4/71
Equipment										
Arrangement number	B	B	B	B	B	B	B	B	B	B
Pressure differentials, mm xylene										
Across nozzle	94	94	94	94	94	94	94	94	94	94
Across plenum (2-6)	46	46	46	46	46	46	46	46	46	46
Atmospheric condition										
Temp, °C	15.5	16.0	15.2	15.0	15.2	14.8	14.2	14.0	13.5	13.0
Barometer, mm Hg	772	772	772	772	772	772	772	772	772	772
Dust type (fly ash)	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ
Feeder										
Groove size	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8
Variac setting	100	100	100	100	100	100	100	100	100	100
RPM	3.27	3.21	3.27	3.23	3.27	3.24	3.24	3.24	3.27	3.24
Filter										
Sampler type	T	T	T	T	T	T	T	T	T	T
Initial filter weight, mg	5.887	5.586	5.626	5.836	6.294	6.070	6.314	6.255	6.157	5.451
Dust collected, mg	0.081	0.261	0.195	0.383	0.280	0.276	0.267	0.221	0.323	0.315
Time, sec	600	600	600	600	600	600	600	600	600	600
Sampling position	3A	3A	2	8	3	5	6	6	5	3
Sampling rate, L/min	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
Aerosol concentration, mg/m ³										
From feed rate	32.6	32.0	32.6	32.3	32.6	32.3	32.3	32.3	32.6	32.6
From filter sample	3.2	10.2	7.65	15.0	11.0	10.6	10.5	8.7	12.7	12.3
Ratio: feeder/filter	9.82	3.14	4.26	2.15	2.96	3.05	3.08	3.71	2.57	2.65
Average transmission reading	0.908	0.905	0.902	0.906	0.906	0.911	0.912	0.912	0.914	0.909
Notes	3			1						

Table C-1 (Continued)

Run Number	21	22	23	24	25	26	27	28	29	30
Date	2/5/71	2/5/71	2/5/71	2/5/71	2/11/71	2/11/71	2/11/71	2/11/71	2/11/71	2/11/71
Equipment	B	B	B	B	B	B	B	B	B	B
Arrangement number										
Pressure differentials, mm										
xylene										
Across nozzle	94	94	94	94	93	93	93	93	93	93
Across plenum (2-6)	46	46	46	46	46	46	46	46	46	46
Atmospheric condition										
Temp, °C	16.0	17.0	15.0	14.8	20.5	25.5	25.2	24.8	25.0	24.8
Barometer, mm Hg	768	768	768	768	771	771	771	771	771	771
Dust type (fly ash)	0-10 μ	C-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ
Feeder										
Groove size	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2
Variac setting	20	20	40	40	20	20	40	40	100	100
RPM	0.292	--	1.07	--	0.324	0.332	1.15	1.15	3.33	3.37
Filter										
Sampler type	T	T	T	T	T	T	T	T	T	T
Initial filter weight, mg	6.335	5.442	6.234	6.314	6.184	6.284	6.025	6.196	6.311	6.334
Dust collected, mg	0.174	0.150	0.240	0.238	0.016	0.217	0.751	0.658	1.606	1.537
Time, sec	3602	3600	1800	1800	830	600	600	600	600	600
Sampling position	3A	3A	3A	3A	3A	3A	3A	3A	3A	3A
Sampling rate, L/min	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
Acrosol concentration, mg/m ³										
From feed rate	2.91	2.91	10.7	10.7	24.2	24.8	84.0	84.0	241.	244.
From filter sample	1.14	0.98	3.14	3.11	0.45	8.5	29.4	25.8	63.0	60.2
Ratio: feeder/filter	2.55	2.97	3.40	3.44	53.8	2.92	2.84	3.26	3.82	4.05
Average transmissionometer reading	--	--	0.966	0.939	0.918	6.924	0.764	0.770	0.482	0.472
Notes		4		4					2	

Table C-1 (Continued)

Run Number	31	32	33	34	35	36	37	38	39	40
Date	2/18/71	2/18/71	2/18/71	2/18/71	2/18/71	2/18/71	2/18/71	2/18/71	2/18/71	2/18/71
Equipment	B	B	B	B	B	B	B	B	B	B
Arrangement number										
Pressure differentials, mm										
xylene	93	93	93	93	93	93	93	93	93	93
Across Nozzle	46	46	46	46	46	46	46	46	46	46
Across plenum (2-6)										
Atmospheric condition										
Temp, °C	15.8	15.8	15.4	15.4	16.2	16.2	16.0	15.7	15.2	15.0
Barometer, mm Hg	770	770	770	770	770	770	770	770	770	770
Dust type (fly ash)	2.5-5 μ	2.5-5 μ	2.5-5 μ	2.5-5 μ	2.5-5 μ	2.5-5 μ	2.5-5 μ	2.5-5 μ	2.5-5 μ	2.5-5 μ
Feeder	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2
Groove size	40	40	40	40	40	40	20	20	100	100
Variat setting	1.05	1.05	1.05	1.05	1.07	1.08	0.297	0.278	3.20	3.23
RPM										
Filter	T	T	T	T	T	T	T	T	T	T
Sampler type	6.200	6.176	5.969	6.171	6.195	6.164	6.130	6.222	5.980	6.167
Initial filter weight, mg	1.302	1.301	0.731	0.770	0.843	0.996	0.281	0.287	2.733	1.898
Dust collected, mg	600	600	600	600	600	600	600	600	600	600
Time, sec	8	8	2	2	3A	3A	3A	3A	3A	3A
Sampling position	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
Sampling rate										
Aerosol concentration, mg/m ³	73.5	73.5	73.5	73.5	74.9	75.6	21.0	19.6	222.	224.
From feed rate	51.0	51.0	28.6	30.2	33.0	39.0	11.0	11.3	107	74.4
From filter sample	1.44	1.44	2.57	2.43	2.27	1.94	1.91	1.74	2.08	3.01
Ratio: feeder/filter										
Average transmissometer reading	0.727	0.734	0.740	0.738	0.734	0.737	0.917	0.920	0.417	0.387
Notes	2				1					2

Table C-1 (Concluded)

Run Number	41	42	43	44	45	46	47	48	49	51	51
Date	2/25/71	2/25/71	2/25/71	2/25/71	2/25/71	2/25/71	2/25/71	2/25/71	2/25/71	2/25/71	2/25/71
Equipment	B	B	B	B	B	B	B	B	B	B	B
Arrangement number											
Pressure, differential mm											
xylene											
Across nozzle	93	93	93	93	93	93	93	93	93	93	93
Across Plonug (2-6)	46	46	46	46	46	46	46	46	46	46	46
Atmospheric condition											
Temp, °C	9.8	10.8	11.4	12.0	12.5	--	13.0	13.3	12.8	12.3	12.6
Barometer, mm Hg	773	773	773	773	773	773	773	773	773	773	773
Dust type (fly ash)	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ
Feeder											
Groove size	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2
Variac setting	20	20	40	100	100	40	40	100	40	40	40
RPM	0.255	0.263	0.983	2.92	2.92	1.05	1.02	3.16	1.04	1.03	1.03
Filter											
Sampler type	T	T	T	T	T	T	T	T	T	T	T
Initial filter weight, mg	6.085	6.153	6.115	6.180	6.114	6.213	6.087	6.179	6.161	6.204	6.226
Dust collected, mg	0.292	0.301	0.927	3.029	2.712	1.240	1.004	2.877	1.008	0.785	0.780
Time, sec	600	600	600	600	600	600	600	600	600	600	600
Sampling position	3A	3A	3A	3A	3A	8	3A	3A	8	2	2
Sampling rate, L/min	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
Aerosol concentration, mg/m ³											
From feed rate	11.8	12.2	45.5	135.2	135.2	48.5	47.2	146.3	48.2	47.7	47.7
From filter sample	11.4	11.8	36.3	118.8	106.3	48.6	39.4	112.8	39.6	30.5	30.6
Ratio: feeder/filter	1.03	1.03	1.25	1.14	1.27	1.00	1.20	1.30	1.22	1.56	1.56
Average transmission											
reading	0.902	0.885	0.652	0.314	0.315	0.586	0.653	0.294	0.654	0.654	0.661
Notes											

Notes: 1. Filter upside down in plastic box before weighing.

2. Some dust adhering to inside lid of filter holder box. Hence dust collected might be recorded as too low.

3. Under microscope this filter contained about 1/4 as much material as filter from run 12 by visual estimate.

4. Feed rate estimated, not measured.

Table C-2

SUMMARY OF SECOND SERIES OF SAMPLING RUNS*

Run Number	52A	52B	53A	53B	54A	54B	55A	55B	56A	56B	57A	57B	58A	58B	59A	59B	60A	60B
Date	8/31/71		9/2/71	9/2/71	9/2/71		9/3/71	9/3/71	9/3/71		9/3/71	9/3/71	9/9/71	9/9/71	9/9/71		9/9/71	
Equipment Arrangement number	B		B	B	B		B	B	B		B	B	B	B	B		B	
Pressure differentials, mm																		
xylene																		
Across nozzle	89		89	89	89		88	87	87		86	91	91	91	91		90	
Across plenum (2-6)	44		43	43	43		43	42	42		41	45	45	45	45		45	
Atmospheric conditions																		
Temp, °C	25.2		27.8	27.8	27.8		28.5	--	--		31.9	21.4	22.2	22.2	22.2		23.2	
Barometer, mmHg	--		762	762	762		761	761	761		761	762	762	762	762		762	
Dust type (fly ash)	0-10 μ		0-10 μ	0-10 μ	0-10 μ		0-10 μ	0-10 μ	0-10 μ		0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ		0-10 μ	
Feeder																		
Groove size	1/16 x 1/8		1/16 x 1/8	1/16 x 1/8	1/16 x 1/8		1/16 x 1/8	1/16 x 1/8	1/16 x 1/8		1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8		1/16 x 1/8	
Variac setting	100		100	100	100		100	100	100		100	100	100	100	100		100	
RPM	3.34		3.28	3.33	3.33		3.40	3.44	3.44		3.43	3.43	3.33	3.33	3.33		3.33	
Filter																		
Sampler type [†]	T	OS	OF	OS	OF	OS	OF	OS	OF	OS	OF	OS	OF	OS	OF	OS	OF	OF
Initial filter weight, mg	6.345	6.400	6.235	6.068	6.894	6.877	6.215	6.095	6.026	6.260	6.203	6.099	6.166	6.006	6.135	6.129	5.965	6.234
Dust collected, mg	0.155	0.525	1.051	0.838	0.694	0.740	0.458	0.365	0.680	0.565	1.058	0.526	0.640	0.470	0.895	0.499	0.063	0.224
Time, sec	707	707	832	832	603	603	659	659	616	616	617	617	600	600	600	600	600	600
Sampling position	2	2	2	2	2	2	2	2	3A	3A	2	2	2	2	2	2	2	2
Sampling rate, l/min	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
Aerosol concentration $\mu\text{g}/\text{m}^3$																		
From feed rate	33.3		32.9	33.2	33.2		34.0	34.3	34.3		34.2	33.2	33.2	33.2	33.2		33.2	
From filter sample	5.16	17.5	29.7	23.7	27.0	28.9	16.4	13.0	25.9	21.6	40.3	20.0	25.1	18.4	35.1	19.5	2.5	8.8
Ratio: feeder/filter	6.45	1.90	1.11	1.39	1.23	1.15	2.07	2.62	1.32	1.59	0.85	1.71	1.32	1.80	0.95	1.70	13.3	3.77
Average transmission reading	0.913		0.908	0.903	0.903		0.905	0.900	0.900		0.900	0.900	0.905	0.905	0.908		0.905	
Notes																		1

* Common conditions: tunnel air flow 5800 CFM including compressed air; compressed air: 50 psi.

† T = copper tube with 90° bend

O = open "delrin"

H₀ = filter horizontal facing up

S = filter facing into stream

F = filter flush with wall

C = closed "delrin"

H₀ = filter horizontal facing down

V = vacuum cleaner bag sampler.

Table C-2 (Continued)

Run Number	61A	61B	62A	62B	63A	63B	64	65A	65B	66A	67A	68A	68B	69A	69B
Date	9/9/71	9/9/71	9/9/71	9/9/71	9/9/71	9/9/71	9/9/71	9/14/71	9/14/71	9/14/71	9/16/71	9/16/71	9/16/71	9/16/71	9/16/71
Equipment	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Arrangement number															
Pressure differentials, mm															
xylene															
Across nozzle	89	89	89	89	89	89	89	86	86	86	88	88	88	87	87
Across plenum(2-6)	43	43	43	43	43	43	43	43	43	43	42	42	42	43	43
Atmospheric conditions															
Temp, °C	28.1	--	--	--	--	--	29.6	35.1	35.1	40.5	27.0	27.2	27.2	26.7	26.7
Barometer, mmHg	762	762	762	762	762	762	762	759	759	759	761	761	761	761	761
Dust type (fly ash)	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ	0-10 μ
Feeder															
Groove size	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8
Variable setting	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
RPM	3.33	3.41	3.41	3.41	3.41	3.41	3.41	3.57	3.57	3.54	3.37	3.37	3.37	3.37	3.37
Filter															
Sampler type**	OF	OH _u	OF	CH _u	CF	CF	OS	OH _u	CH _u	OH _u	CH _u	OH _u	CH _u	OH _u	CH _u
Initial filter weight, mg	6.196	6.160	6.184	6.189	6.090	6.102	6.244	5.516	5.768	5.609	6.079	6.253	6.133	5.775	5.766
Dust collected, mg	0.475	0.691	0.198	0.527	0.220	0.381	0.014	0.610	0.516	0.518	0.412	0.387	0.252	0.471	0.486
Time, sec	600	600	600	600	600	600	46	736	736	600	600	600	600	600	600
Sampling position	3A	3A ₁	3A	3A ₁	7	8	3A ₁	3A _c	3A _c	3A _c	3A _c	3A _c	3A _c	3A _c	2 _c
Sampling rate, l/min	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
Aerosol concentration mg/m ³															
From feed rate	33.2	31.0	31.0	34.0	34.0	31.0		35.6	35.6	35.2	33.6	33.5	33.5	33.6	33.6
From filter sample	18.6	27.1	19.5	20.7	8.6	15.0	--	20.5	17.5	20.3	16.2	15.2	9.9	18.5	19.1
Ratio: feeder/filter	1.79	1.22	1.71	1.64	3.95	2.26	--	1.74	2.04	1.77	2.18	2.21	3.39	1.82	1.76
Average transmission reading	0.905	0.905	0.905	0.908	0.908	0.910		0.913	0.913	0.911	0.920	0.925	0.925	0.907	0.907
Notes							2								3

Table C-2 (Continued)

Run Number	70A	70B	71A	71B	72A	72B	73A	73B	74A	74B	75A	75B	76A	76B	77A	77B	78A	78B
Date	9/20/71		9/20/71		9/20/71		9/20/71		9/27/71		9/27/71		9/27/71		9/27/71		9/28/71	
Equipment	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Arrangement number																		
Pressure differentials, mm																		
xylene																		
Across nozzle	87	87	87	87	87	87	86	86	90	90	--	--	89	89	--	--	89	89
Across plenum(2-6)	43	43	43	43	43	43	44	44	44	44	--	--	44	44	--	--	44	44
Atmospheric conditions																		
Temp, °C	23.0	23.0	23.0	23.0	23.0	23.0	22.5	22.5	21.6	21.6	21.9	21.9	21.9	21.9	21.9	21.9	18.8	18.8
Barometer, mmHg	763	763	763	763	763	763	763	763	766	766	766	766	766	766	766	766	764	764
Dust type (fly ash)	5-10 μ	5-10 μ	5-10 μ	5-10 μ	5-10 μ	5-10 μ	5-10 μ	5-10 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	0-2.5 μ	2.5-5 μ	2.5-5 μ
Feeder																		
Groove size	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8
Variac setting	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
RPM	3.26	3.26	3.26	3.26	3.26	3.26	3.27	3.27	3.22	3.22	3.17	3.17	3.27	3.27	3.23	3.23	3.20	3.20
Filter																		
Sampler type**	OH _u	CH _u	OH _u	CH _u	OH _u	CH _u	OH _u	CH _u	OH _u	CH _u	OH _u	CH _u	OH _u	CH _u	OH _u	CH _u	OH _u	CH _u
Initial filter weight, mg	6.176	5.708	5.566	6.183	5.761	6.070	5.567	5.953	5.936	6.045	5.539	6.016	6.094	5.569	5.951	5.878	6.124	5.658
Dust collected, mg	0.438	0.413	0.492	0.326	0.761	0.299	0.705	0.345	0.425	0.413	0.532	0.449	0.462	0.436	0.494	0.451	0.466	0.440
Time, sec	600	600	600	600	600	600	600	600	596	596	638	638	653	653	611	611	538	538
Sampling position	3A _c	3A _c	3A _c	2 _c	2 _c	2 _c	2 _c	2 _c	3A _c	3A _c	2 _c	2 _c	3A _c	3A _c	2 _c	2 _c	3A _c	3A _c
Sampling rate, l/min	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
Aerosol concentration mg/m ³																		
From feed rate	31.3	31.3	31.3	31.3	31.3	31.3	31.4	31.4	16.7	16.7	16.4	16.4	16.9	16.9	16.7	16.7	27.2	27.2
From filter sample	17.2	16.2	19.3	12.8	29.9	11.7	27.6	13.9	16.8	16.3	19.6	16.5	16.6	15.7	19.0	17.3	17.2	16.2
Ratio: feeder/filter	1.82	1.93	1.62	2.44	1.05	2.68	1.14	2.26	1.00	1.02	0.84	1.00	1.02	1.08	0.88	0.97	1.58	1.68
Average transmissometer reading	0.955	0.945	0.945	0.950	0.950	0.950	0.945	0.945	0.863	0.863	0.860	0.860	0.863	0.863	0.855	0.855	0.840	0.840
Notes																		

Table C-2 (Continued)

Run Number	79A	79B	80A	80B	81A	81B	82A	82B	83A	83B	84A	84B	85A	85B	86A	86B	87A	87B
Date	9/28/71	9/28/71	9/28/71	9/28/71	9/28/71	9/28/71	9/29/71	9/29/71	9/29/71	9/29/71	9/29/71	9/29/71	9/29/71	9/29/71	9/29/71	9/29/71	10/8/71	
Equipment	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Arrangement number																		
Pressure differentials, mm																		
xylene																		
89			89		89		--	--	--	--	89		--	--	89		90	
45			45		43		--	--	--	--	44		--	--	44		43	
Across nozzle																		
Across plenum(2-6)																		
Atmospheric conditions																		
Temp, °C	18.3		--		22.5		--	--	--	--	23.0		21.0		20.5		24.4	
Barometer, mmHg	764		764		762		--	--	--	--	--		--		--		765	
Dust type (fly ash)	2.5-5μ		2.5-5μ		5-10μ		9-10μ		5-10μ		5-10μ		5-10μ		5-10μ		5-10μ	
Feeder																		
Groove size	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	
Varial setting	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	
RPM	3.19	3.28	3.28	3.28	3.24	3.24	3.25	3.25	3.28	3.28	3.26	3.26	3.30	3.30	3.30	3.30	3.25	
Filter																		
Sampler type**	OH	CH	OH	CH	OH	CH	OH	CH	OH	CH	OH	CH	OH	CH	OH	CH	OH	OS
Initial filter weight, mg	5.750	5.621	6.054	5.711	5.842	5.569	5.623	5.645	5.082	5.665	5.654	5.586	5.974	5.645	6.037	5.925	5.736	12.913
Dust collected, mg	0.536	0.464	0.447	0.423	0.453	0.361	0.473	0.315	0.524	0.322	0.442	0.244	0.884	0.899	1.190	1.260	0.659	0.549
Time, sec	645		600		600		627		600		615		1200		1200		612	
Sampling position	2 _c	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A	3 _A
Sampling rate, l/min	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
Aerosol concentration mg/m ³																		
From feed rate	27.2	27.9	27.9	27.9	32.1	32.1	32.2	32.2	32.5	32.5	32.3	32.3	32.7	32.7	32.7	32.7	32.3	
From filter sample	19.5	16.9	17.5	16.6	17.7	14.1	17.7	11.8	20.5	12.6	16.9	9.3	17.3	17.6	23.3	24.7	25.3	21.1
Ratio: feeder/filter	1.39	1.61	1.59	1.68	1.81	2.28	1.82	2.73	1.58	2.58	1.91	3.47	1.89	1.86	1.40	1.32	1.28	1.53
Average transmission	0.81	0.875	0.875	0.875	0.950	0.950	0.955	0.955	0.918	0.918	0.946	0.946	0.943	0.943	0.941	0.941	0.947	
reading																		
Notes																		

Table C-2 (Continued)

Run Number	88A	88B	89A	89B	90A	90B	91A	91B	92A	92B	93A	93B	94A	94B	95	96
Date	10/8/71	10/8/71	10/8/71	10/8/71	10/8/71	10/8/71	10/12/71	10/12/71	10/12/71	10/12/71	10/12/71	10/12/71	10/12/71	10/12/71	10/18/71	10/18/71
Equipment	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Arrangement number																
Pressure differentials, mm																
xylene																
Across nozzle	90	90	90	90	90	90	91	91	91	91	87	87	88	88	90	90
Across plenum (2-6)	43	43	43	43	43	43	44	44	44	44	42	42	42	42	44	44
Atmospheric conditions																
Temp, °C	23.3	21.9	21.9	21.2	21.2	21.2	18.0	18.0	20.9	20.9	32.9	32.9	32.7	32.7	18.8	18.8
Barometer, mmHg	765	765	765	765	765	765	763	763	763	763	764	764	764	764	764	764
Dust type (fly ash)	5-10 μ	5-10 μ	5-10 μ	5-10 μ	5-10 μ	5-10 μ	5-10 μ	5-10 μ	5-10 μ	5-10 μ	2.5-5 μ	2.5-5 μ	2.5-5 μ	2.5-5 μ	2.5-5 μ	2.5-5 μ
Feeder																
Groove size	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8	1/16 x 1/8
Variac setting	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
RPM	3.31	3.27	3.27	3.27	3.27	3.27	3.23	3.23	3.27	3.27	3.27	3.27	3.43	3.43	3.17	3.23
Filter																
Sampler type**	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	OS	V
Initial filter weight, mg	5.936	12.282	6.029	17.813	5.558	12.506	5.724	5.960	5.914	5.924	5.593	6.105	5.546	5.546	13710	13680
Dust collected, mg	0.608	0.648	0.587	0.626	0.597	0.829	1.891	1.360	2.692	1.557	2.021	1.868	1.280	1.639	240	270
Time, sec	606	600	600	600	600	600	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
Sampling position	3A _C	3A _C	3A _C	3A _C	3A _C	3A _C	3A _C	3A _C	3A _C	3A _C	3A _C	3A _C	3A _C	3A _C	3A _C	3A _C
Sampling rate, l/min	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
Aerosol concentration mg/m ³	32.8	32.4	32.4	32.4	32.4	32.4	32.0	32.0	32.4	32.4	28.7	28.7	29.2	29.2	27.5	27.5
From feed rate	23.6	25.1	23.0	24.5	23.4	32.4	24.7	17.8	35.2	20.3	26.4	24.4	16.7	21.4	16.3	14.7
From filter sample	1.39	1.31	1.41	1.32	1.38	1.00	1.30	1.80	0.92	1.60	1.09	1.17	1.75	1.36	1.66	1.87
Ratio: feeder/filter																
Average transmission	0.946	0.948	0.948	0.948	0.948	0.948	0.949	0.949	0.942	0.942	0.860	0.860	0.850	0.850	0.90	0.88
reading																
Notes	5	5	5	5	5	5									6, 7	6

Table C-2 (Concludes)

Run Number	97	98	99	100	101	102
Date	10/19/71	10/19/71	10/26/71	10/26/71	10/26/71	10/26/71
Equipment	B	B	B	B	B	B
Arrangement number						
Pressure differentials, mm xylene						
Across nozzle	91	91	92	--	--	--
Across plenum (2-6)	44	44	44	--	--	--
Atmospheric conditions						
Temp, °C	18.8	21.0	14.0	--	--	--
Barometer, mmHg	769	769	763	763	763	763
Dust type (fly ash)	5-10 _μ	5-10 _μ	5-10 _μ	5-10 _μ	5-10 _μ	5-10 _μ
Feeder						
Groove size	1/16 x 1/8	1/16 x 1/8	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2	1/8 x 1/2
Variable setting	100	100	20	40	100	40
RPM	3.30	3.33	0.227	1.00	3.08	1.04
Filter						
Sampler type**	V	V	--	--	--	--
Initial filter weight, mg	13640	13790	--	--	--	--
Dust collected, mg	390	320	--	--	--	--
Time, sec	1800	1800	--	--	--	--
Sampling position	3A _C	3A _C	--	--	--	--
Sampling rate, l/min	660	497	--	--	--	--
Aerosol concentration mg/m ³						
From feed rate	32.7	33.0	18.1	73.0	206.	75.9
From filter sample	19.7	21.5	--	--	--	--
Ratio: feeder/filter	1.65	1.53	--	--	--	--
Average transmission reading	0.93	0.91	0.969	0.875	0.666	0.870
Notes	6	6				

Notes: 1. Filter mounted over side of tunnel (not over a hole).

2. Dummy run in which filter was moved into tunnel facing stream with no air flow through filter. Time given is total exposure time.

3. Manometer across filter blew out when run was 1/2 to 2/3 over.

4. Major drift experienced in transmission meter zero.

5. In the "b" runs, a special composite filter was used: 1) top of Nuclepore containing four 1/8" holes with shiny side up; 2) bottom Nuclepore with matte side up; 3) the two spot glued with Buco cement and separated at center with small piece of Nuclepore paper.

6. Sample taken with vacuum cleaner with 1" rounded nozzle pointed into air stream leading directly to paper vacuum cleaner bag (approx. 1 sq. ft. area). Pressure drop across inlet nozzle used to meter air flow rate.

7. Feed rate dropped erratically during last half of run, apparently due to bridging in feeder hopper.

Table C-3

SUMMARY OF CONCENTRATION RATIO DATA FOR SAMPLING AND FILTER ARRANGEMENT "T"

Feeder Conditions			Concentration Ratio, $\left(\frac{\text{Feeder}}{\text{Filter}}\right)$ At Location Number*						Sampling Run Number
Dust Fraction	Groove Size	Speed Control Setting	2	3	3A	5	6	8	
0-2.5 μ	1/8 x 1/2	20			1.03				41
					1.03				42
		40	1.56		1.25			1.00	50, 43, 46
			1.56		1.20			1.22	51, 47, 49
		100			1.14				44
					1.27				45
					1.30				48
2.5-5 μ	1/8 x 1/2	20			1.91				37
					1.74				38
		40	2.57		2.27			1.44	33, 35, 31
			2.43		1.94			1.44	34, 36, 32
		100			2.08				39
					3.01				40
0-10	1/16 x 1/8	20	6.45		2.55				52A, 21
					2.97				22
		40			3.40				23
					3.44				24
		100	3.35	2.18	9.62	3.43	5.00	2.35	1, 5, 11, 7, 3, 9
			3.94	2.09	3.14	2.91	5.53	2.15	2, 6, 12, 8, 4, 14
			4.38	2.96		3.05	3.08		10, 15, 16, 17
			4.26	2.65		2.57	3.71		13, 20, 19, 18
	1/8 x 1/2	20			53.8				25
					2.92				26
		40			2.84				27
					2.26				28
		100			3.82				29
					4.05				30

* See Figure C-4 for position corresponding to each location number.

Table C-4

SUMMARY OF CONCENTRATION RATIO DATA FOR SECOND SERIES OF SAMPLING RUNS
 Conditions Common to all Runs--Groove Size: 1/16 x 1/8
 Speed Control Setting: 100

Dust Fraction	Sampling Location Number	Concentration Ratio (Feeder/Filter)									Sampling Run Number
		For Sampler Type and Arrangement Number*									
		OF	CF	OS	CS	OH _u	CH _u	OH _d	CH _d	V	
0-2.5 _μ	2 _c					0.84	1.00				75A, 75B
						0.88	0.97				77A, 77B
	3A _c					1.00	1.02				74A, 74B
						1.02	1.08				76A, 76B
2.5-5 _μ	2 _c					1.39	1.61				79A, 79B
	3A _c			1.09		1.58	1.68			1.66	93A, 78A, 78B, 95
				1.75		1.59	1.68			1.87	94A, 80A, 80B, 96
						1.17					93B
						1.36					94B
5-10 _μ	2 _c					1.05	2.68				72A, 72B
						1.14	2.26				73A, 73B
	3A _c			1.89	1.86	1.82	1.93	1.58	2.58	1.66	85A, 85B, 70A, 70B, 83A, 83B, 97
				1.40	1.32	1.62	2.44	1.91	3.47	1.53	86A, 86B, 71A, 71B, 84A, 84B, 98
				1.28		1.81	2.28				87A, 81A, 81B
				1.53		1.82	2.73				87B, 82A, 82B
				1.39		1.41					88A, 89A
				1.31		1.32					88B, 89B
				1.30		1.38					91A, 90A
				0.92		1.00					92A, 90B
						1.80					91B
						1.60					92B
											53A
											54A
											57A
											58A
											59A
	2 ₁			1.90							52B
				1.39							53B
				1.15							54B
	2 ₂			1.71							57B
				1.80							58B
2 _c			1.70		1.23	1.59				59B, 69A, 69B	
3A	2.07									55A	
	1.32									56A	
	1.79									61A	
	1.74									62A	
3A ₁				2.62		1.22	2.64				55B, 61B, 62B
				1.59							56B
						1.74	2.04				65A, 65B
						1.73	2.18				66A, 66B
						2.21	3.39				67A, 67B
						1.82	1.76				68A, 68B
											60B, 63A
											60A, 63B
	7	3.77	3.95								
	8	13.3†	2.26								

* Symbols used as follows:

Sampler Orientation: F = flush with wall
 S = facing into nominal air stream (medium vertical)
 H_d = filter medium horizontal facing down
 H_u = filter medium horizontal facing up.

Type sampler: O = open "Delrin"
 C = closed "Delrin"
 V = vacuum cleaner bags (vertical intake).

† Questionable run.

Table C-5
SUMMARY OF WEATHER MEASURE SAMPLING DATA

Date	Equipment Arrangement Number	1/28/71	2/3/71				2/11/71				2/18/71			
	Dust Fraction (Fly Ash)	A	B				B				B			
	Feeder, Groove Size	0-10μ	0-10μ				0-10μ				2.5-5μ			
	Speed Control Setting	1/16 x 1/8	1/16 x 1/8				1/8 x 1/2				1/8 x 1/2			
	Dispenser Air Pressure, psig	100	50	10	20	30	50	20	40	100	20	40	100	
	Sampling Rate, * liters/min	40"	50	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	
	Nominal Dust Concentration, † mg/m³	32	32	32	32	32	32	32	24	84	24	84	20	
	Weather Measure Readings, ‡ counts/min												222	
At Sampling Location														
Equipment	Section	Number												
Plenum	Supply Line	9												
		10												
		7												
		8												
		12												
Sighting Tunnel		13												
		6												
		5												
		5A												
		16												
Atmospheric Air		4												
		42												
		49												
		14												
		36												
Atmospheric Air		25, 27												
		20												
		28												
		21, 25, 29												
		28												
Atmospheric Air		35, 28, 26												
		30, 27, 21												
		9												
		34, 21, 40												
		37, 39, 32												
Atmospheric Air		42, 29, 39												
		46, 38, 37												
		48												
		3.2												
		32												
Atmospheric Air		31, 34												
		322(246)												
		390(316)												
		272(286)												
		90(86)												
Atmospheric Air		44, 45												
		448(446)												
		508(516)												
		34, 32												
		97(106)												
Atmospheric Air		102(96)												
		294(276)												
		32												
		342(326)												
		474(420)												
Atmospheric Air		52, 47												
		502(470)												
		51												
		508(516)												
		32												

* Except where otherwise noted, Weather Measure Instrument exhaust was connected to the atmosphere.

* Except where otherwise noted, Weather Measure Instrument exhaust was connected to the same metered vacuum system as was used for the filter sampling runs.
 ** In this case instrument was exhausted to the atmosphere with the plenum pressure acting to cause flow through the instrument; the flow rate given is estimated.
 † Not measured in these runs but estimated from feeder rates measured during filter sampling runs at the same feeder groove and speed control setting.
 †† Values given are those determined by noting total count and corresponding elapsed time. The count rate is then calculated. The value recorded is this calculated rate after subtracting 4 counts/min which had previously been established as a background level with filtered air. At above 100 counts/min, the counting rate could also be read directly on the instrument; such rates are noted in parentheses () also corrected for a background count of 4.

Appendix D

AEROSOL CHAMBER OPTICAL COMPONENTS

The fly ash aerosol generated with the especially designed and assembled equipment described in Appendix A was continuously monitored by a white-light source transmissometer and, during periods of low background conditions, by 90° light scatter from a small portion of the transmissometer light beam (Figure D-1). The transmissometer was designed to minimize the forward-scattering problem associated with light extinction measurements (Zuev, 1966). Light transmission T is defined in terms of Bouguer's (Beer's) Law as:

$$T = \frac{I}{I_0} = e^{-\sigma L}$$

where

- I_0 = light intensity in absence of an attenuating medium
- I = measured light intensity
- L = path length along the interacting medium
- σ = volume extinction coefficient.

However, the light intensity I may contain some light that has been scattered by the attenuating medium, resulting in an apparent extinction coefficient (σ_a) smaller than the true coefficient (σ). The ratio of these

* ZUEV, V. E., 1966: Atmospheric transparency in the visible and infrared. Translated from Russian, available from the Clearinghouse for Federal Scientific and Technical Information (TT69-55102).

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coefficients depends on the transmissometer geometry (primarily path length and receiver aperture) and the angular scattering function of the aerosol. Since larger particles (with respect to the light wavelength) are more efficient forward scatters, σ_a will have largest deviation from σ for the larger fly ash fractions. A transmissometer receiver aperture of 2.5 in. and a light beam width and receiver field-of-view of only 6 mrad were used to minimize the forward scattering problem.

The transmissometer is calibrated in terms of mass concentration, M , by means of the particle feed rates. Since the largest fractions are more susceptible to mass concentration losses because of particle settling, less mass may be expected than is recorded. Hence, the apparent extinction coefficient may best relate to the true particle density (mass concentrations) within the aerosol chamber.

Figure D-2 is a data flow diagram of the optical scattering sensors. A spectral filter was inserted in the transmissometer receiver (Figure D-1) to approximate the spectral response of the eye. The transmissometer linearity was checked by inserting neutral density filters in the beam path and was found to be linear within 1% of the output reading. After each backscatter experiment the current supplied to the light source was adjusted by a voltage measurement across a precision resistor and the output of the operational amplifier was adjusted for a voltage reading of between 0.995 and 1.000 with a "clean air" chamber. The light source current was monitored for stability during each experiment. The transmission data were recorded on a strip chart recorder (1 mm/sec) for a continuous, but relatively low accuracy, time record of aerosol transparency and by a higher accuracy paper tape printout at predetermined times. An example of the data records is shown in Figure D-3. Event marks were placed on one side of the strip chart recorder when a lidar firing pulse was received from a communications line between the lidar and chamber sites.

Event marks on the opposite side of the chart indicate both lidar firings and pulses signifying one revolution of the particle feeder disk. For each of these event marks, a value of transmission (voltage) was printed on the paper tape record.

The 90° side-scatter data were recorded in relative logarithmic units on a second channel of the strip chart recorder. However, because of high background light levels during daytime, these data were of only limited use. Since the transmissometer views a much larger aerosol volume than the side-scatter photometer, the relative variations between these outputs are indicators of aerosol homogeneity. Larger variations were normally observed in the transmissometer output indicating the aerosol was well dispersed within the chamber.

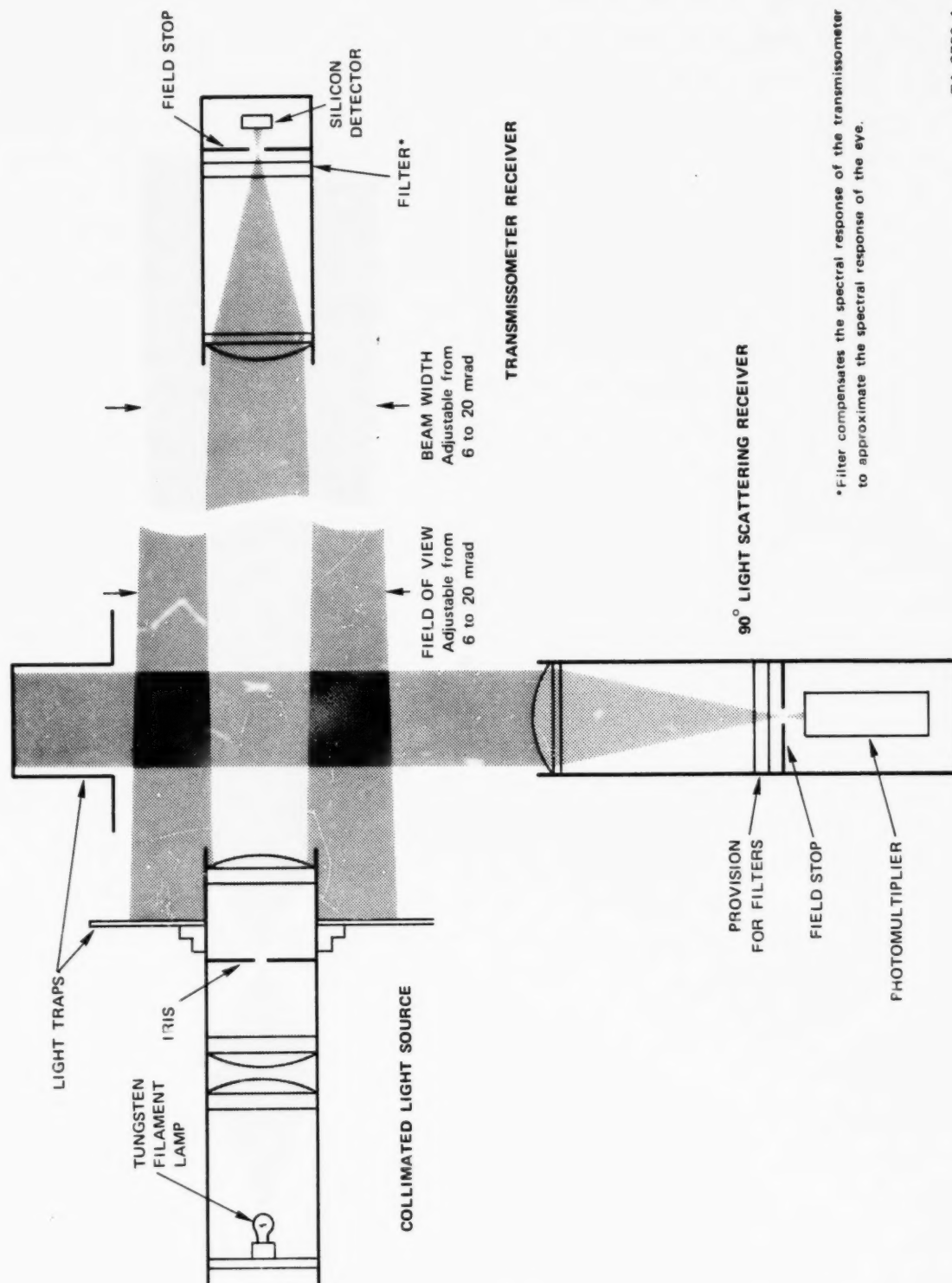
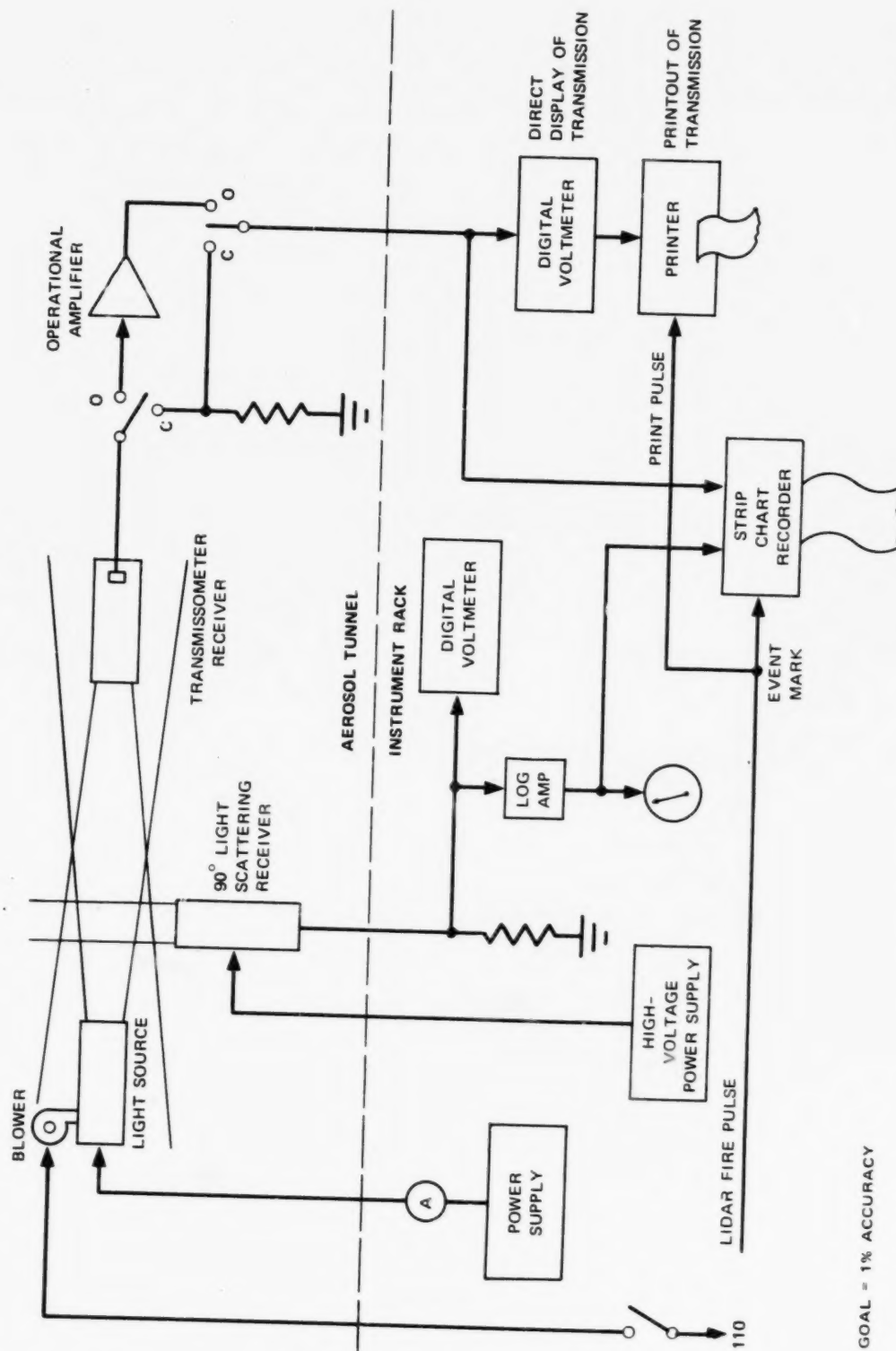


FIGURE D-1 OPTICAL DIAGRAM OF THE TRANSMISSOMETER AND ANGULAR SCATTERING SENSORS

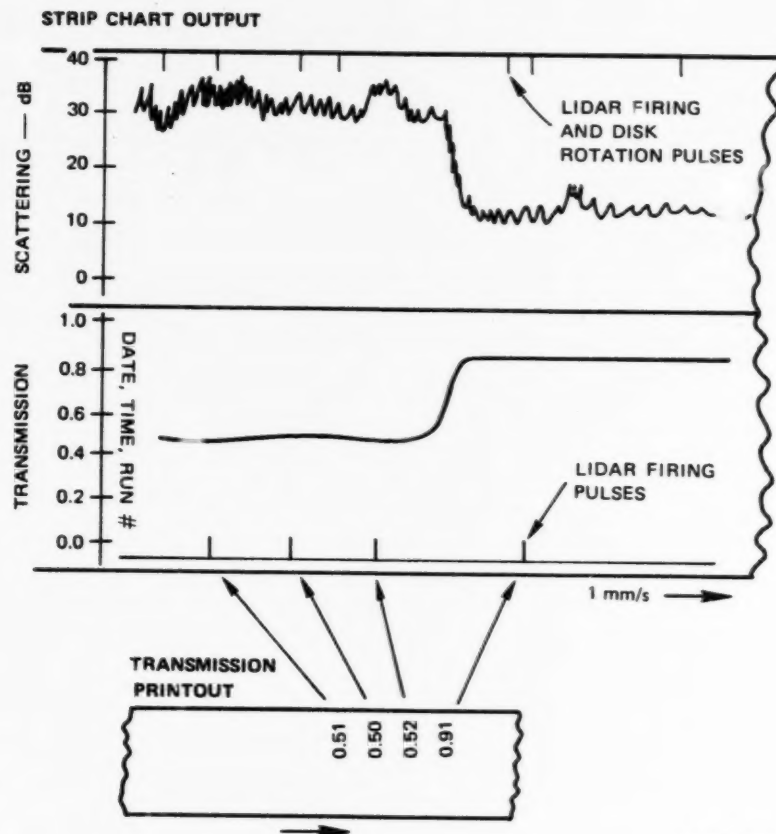
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GOAL = 1% ACCURACY

TA-8730-5

FIGURE D-2 DATA FLOW DIAGRAM OF THE OPTICAL SCATTERING SENSORS



TA-8730-6

FIGURE D-3 DATA FORMAT OF THE OPTICAL SCATTERING SENSORS

Appendix E

TRANSMISSOMETER DATA

Transmissometer readings were taken at all times when the sighting tunnel was in operation. This appendix presents and analyzes all data showing the relationship between the optical transmission measurements made in the tunnel and the aerosol concentration for the various aerosols. Details of the transmissometer construction and operation are given in Appendix D while details of simultaneous concentration and transmission measurements are given in Appendix C.

Background Theory

Basic Optical Transmission Equations

Optical performance is usually measured in terms of a scattering coefficient defined by the Beer's relationship:

$$dI = -\sigma I dL \quad (E-1)^*$$

The gross geometry of an aerosol system can be allowed for by introducing an efficiency factor, Q_e , defined as

$$\sigma = \sum_{n=0}^{n=\infty} p_n Q_e \left(\pi D_p^2 / 4 \right) \Delta n_p \quad (E-2)$$

* A table of nomenclature is given at the end of this appendix.

The factor, Q_e , is a function of the ratio of particle size to wavelength of light used (D_p/λ) and the refractive index of the particle (m). For spherical particles this functional relationship is given by the well-known Mie theory.

Thus, although Q_e is a function of particle size, for many practical purposes it is convenient to write Equation E-2 in terms of an average efficiency factor

$$\sigma = Q_{e_{av}} \sum_{n=0}^{n=n_p} (\pi D_p^2 / 4) \Delta n_p \quad (E-3)$$

where, by definition,

$$Q_{e_{av}} = \frac{\sum Q_e D_p^2 \Delta n_p}{\sum D_p^2 \Delta n_p} \quad (E-4)$$

The advantage of so defining $Q_{e_{av}}$ is that, as will be shown later, $Q_{e_{av}}$ will be dependent primarily on some mean particle diameter when dealing with a mixture of particle sizes.

Mean Particle Diameters

A mixture of particle sizes can be represented by any one of an infinite number of mean sizes. Mean size can generally be defined in the following format:

$$\bar{D}_{qj} = \left[\frac{\sum D_p^q \Delta n_p}{\sum D_p^j \Delta n_p} \right]^{[1/(q-j)]} \quad (E-5)$$

Certain specific mean sizes will be of special significance in expressing transmission performance. The "surface mean" diameter (sometimes

called the "surface-to-number" mean) corresponds to values of 2 and 0 for q and j, respectively,

$$\bar{D}_{20} = \left[\frac{\sum D_p^2 \Delta n_p}{\sum \Delta n_p} \right]^{1/2} \quad (E-6)$$

The "Sauter" diameter (sometimes called the "volume-to-surface" mean) corresponds to values of 3 and 2 for q and j, respectively,

$$\bar{D}_{32} = \frac{\sum D_p^3 \Delta n_p}{\sum D_p^2 \Delta n_p} \quad (E-7)$$

But, since, by definition,

$$w_p = \sum (\pi \rho_p / 6) D_p^3 \Delta n_p \quad (E-8)$$

Equation E-7 may also be written as

$$\bar{D}_{32} = \frac{(6w_p / \pi \rho_p)}{\sum D_p^2 \Delta n_p} \quad (E-9)$$

if all particles have the same density. If the particles' density varies, ρ_p may be defined as an "average" particle density.

Applied Optical Equations

By combining Equations E-1 and E-3 with Equation E-6 and E-9, respectively, optical performance can be written in two alternate formats:

a) In terms of particle number concentration:

$$dI = -(\pi/4)Q_{e_{av}} n_p \bar{D}_{20}^2 IdL \quad (E-10)$$

or

$$\ln(1/T) = \ln(I_o/I) = (\pi/4)Q_{e_{av}} n_p \bar{D}_{20}^2 L \quad (E-11)$$

b) In terms of particle mass concentration:

$$dI = -(3/2)Q_{e_{av}} (w_p/\rho_p \bar{D}_{32}) IdL \quad (E-12)$$

or

$$\ln(1/T) = \ln(I_o/I) = (3/2)(Q_{e_{av}} w_p/\rho_p \bar{D}_{32}) L \quad (E-13)$$

It will be observed that when concentrations are measured in terms of particle number, the optical performance is dependent on the square of the mean diameter $\bar{D}_{20}$; when measured in terms of mass, it is dependent only on the first power of the mean diameter $\bar{D}_{32}$. In this study mass concentration of aerosol was determined as well as the Sauter diameter, $\bar{D}_{32}$, for each fraction. Consequently, these values in conjunction with the measured values of light transmission can be used to evaluate $Q_{e_{av}}$.

Experimental Results

The runs in which both aerosol concentration and transmission values were established are discussed in Appendix C. These results are summarized in Table E-1. Average values of aerosol concentration and optical transmission are given in Table E-1 for all runs made at nominally the same conditions and with the same aerosol.

As discussed in Appendix C, aerosol concentrations calculated from the measured feeder disk speed are believed to be the most reliable measure of aerosol concentration. Consequently, for this comparison with optical transmission, only the aerosol concentration values established from feeder disk speeds will be used.

The data of Table E-1 are shown plotted in alternate forms in Figures E-1 and E-2. In Figure E-1 the transmission (on a log scale) is plotted against the mean dust concentration (on an arithmetic scale) for each dust fraction. As expected from Equation E-13, straight lines are obtained for each dust, with the finest dust being optically the most active. The upper scale expresses concentration in grains/cu ft to permit each comparison with units used in practice.

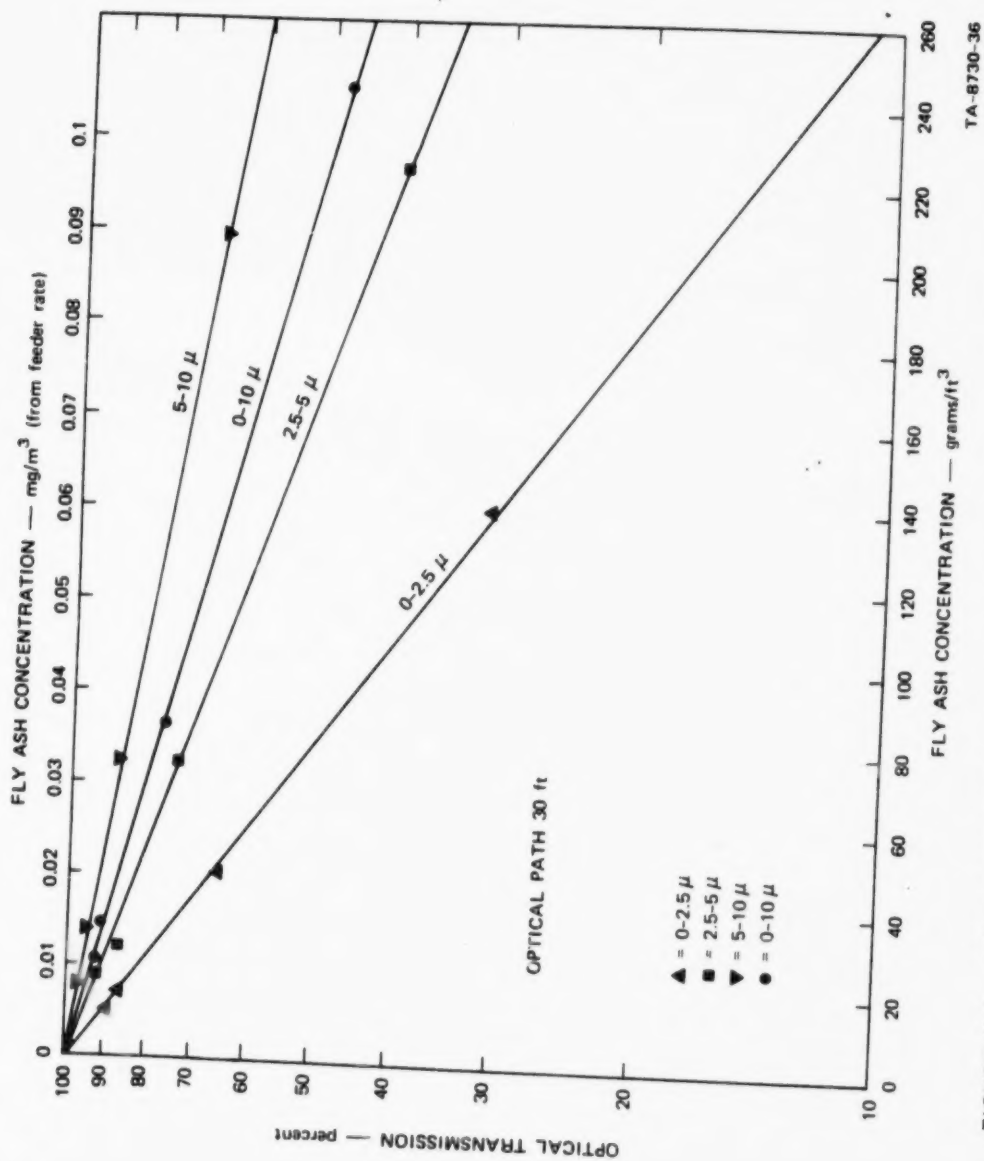
In order to permit a more quantitative evaluation of the effect of particle size, the data are plotted in Figure E-2 as transmission (on a log scale) against the grouping $3Lw_p / 2\rho_p \bar{D}_p^2$ (termed effective opacity) on an arithmetic scale. The slope of such a plot is the average efficiency factor. Lines for values of $Q_{e_{av}}$ of 1, 2, and 3 are shown as dashed. The data can all be correlated within the actual precision by the single solid line. This line corresponds to an average efficiency factor of approximately 2.4. Although there appears to be a trend in the data for the various fractions toward higher $Q_{e_{av}}$ values with reduced particle size (as expected from theory for this particle size range), these trends are believed to be outside of the overall intrinsic precision.

The average efficiency factor calculated for each data point is shown in the last column of Table E-1. Because of errors in the individual values that go into the calculation of $Q_{e_{av}}$, these values for the individual points will tend to exaggerate discrepancies. In general, however, these values agree well with the value of 2.4 deduced from Figure E-2.

Values of $Q_{e_{av}}$ have been calculated for each of the dust fractions. To do this, the size distributions given in Appendix B, Table B-4 were used in conjunction with Mie theory to define Q_e and the operation indicated by Equation E-4 was made on a CDC-6400 computer. Such calculations were made for two assumed wavelengths of light, 0.7 and 1.06 μ . The results of the calculations, shown in Table E-2, show excellent agreement with the experimental results for the transmissometer.

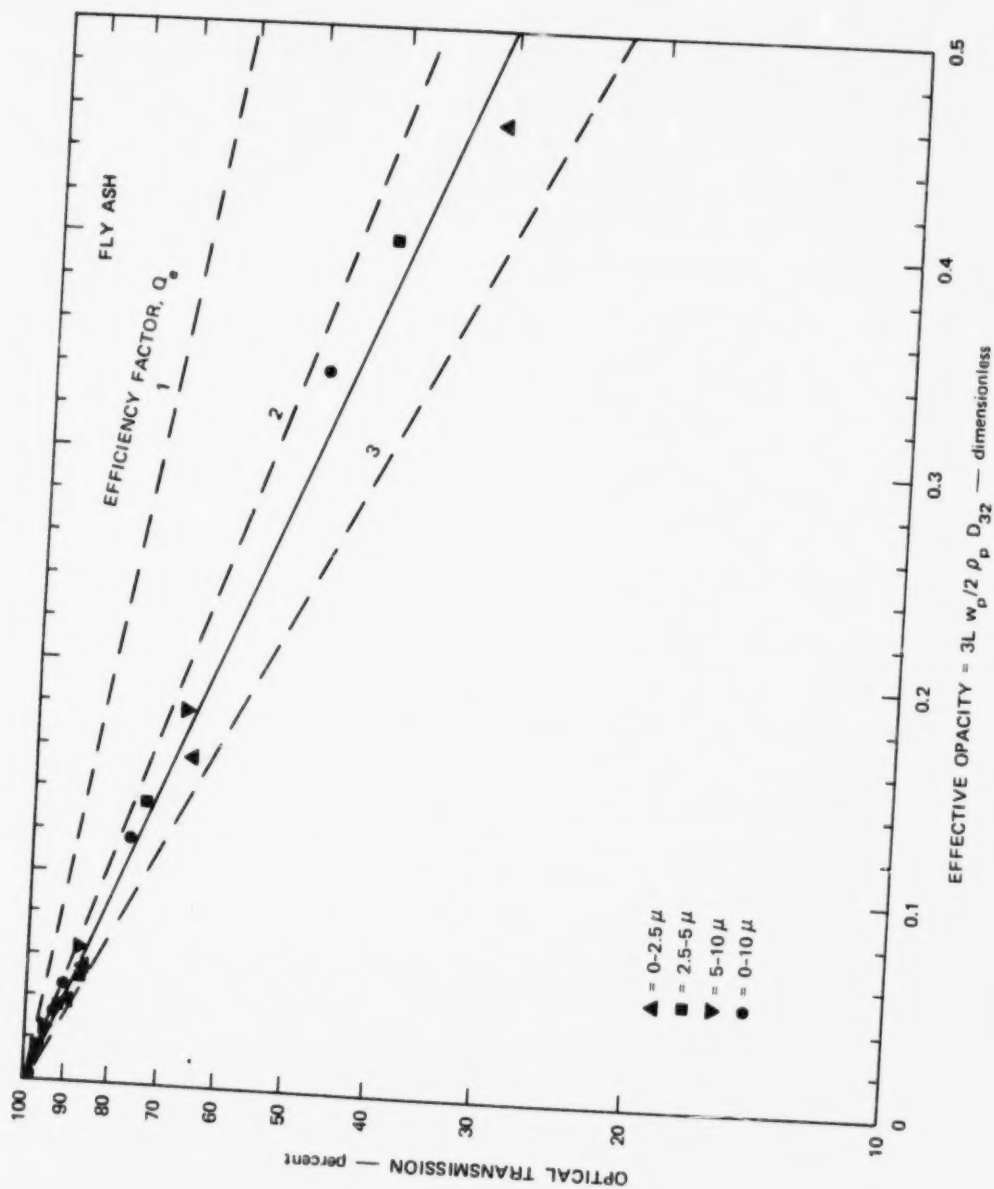
NOMENCLATURE

- D_p = particle diameter, cm
 $\bar{D}_{qj}$ = any mean particle diameter, cm
 $\bar{D}_{20}$ = surface-mean particle diameter, cm
 $\bar{D}_{32}$ = Sauter diameter, cm
 I = incident light intensity, lumens/sq. cm
 I_o = initial incident light intensity, lumens/sq. cm
 L = optical path length, cm
 m = refractive index, dimensionless
 n_p = particle number concentration, number/cm³
 q, j = dimensionless integers
 Q_e = cross section efficiency factor, dimensionless
 $Q_{e\text{ av}}$ = average efficiency factor, dimensionless
 T = fractional light transmission = I/I_o
 w_p = particle mass concentration grams/cm³
 ρ_p = true particle density, grams/cm³
 σ = scattering coefficient, cm⁻¹
 σ_g = standard geometric deviation, dimensionless
 λ = wavelength of light, cm



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FIGURE E-1 EFFECT OF FLY ASH CONCENTRATION AND SIZE ON OPTICAL TRANSMISSION



TA-8730-37

FIGURE E-2 GENERALIZED CORRELATION FOR OPTICAL TRANSMISSION

Table E-1
SUMMARY OF TRANSMISSOMETER DATA

Fly Ash Fraction Used [†]	Mean Diameter [†] $\bar{D}_{32}$ Microns	Feeder Conditions		Feeder Disk Speed RPM	Average Results [‡]			Effective Opacity ($3L_w/2cD_{32}$) Dimensionless	Average Efficiency Factor [§] Q_{eav} Dimensionless
		Groove Size	Speed Control Setting		Dust Concentration [‡] mg/m^3	Optical Transmission %	Data from Run Numbers		
0-2.5 μ	1.7	1/16 x 1/8	100	3.22	16.7	86.0	74-77	0.0550	2.73
		1/8 x 1/2	20	0.259	12.0	89.2	41-42	0.0395	2.89
			40	1.00	47.0	65.5	43, 46, 47, 49-51	0.1545	2.73
			100	3.00	138.9	30.8	44, 45, 48	0.456	2.58
2.5-5 μ	3.1	1/16 x 1/8	100	3.27	27.8	86.4	78-80, 93-96	0.0501	2.91
		1/8 x 1/2	20	0.288	20.3	91.8	37, 38	0.0366	2.35
			40	1.06	74.1	73.5	31-36	0.1336	2.30
			100	3.22	223.	40.2	39, 40	0.401	2.27
5-10 μ	6.5	1/16 x 1/8	100	3.27	32.3	94.6	70-73, 81-92, 97, 98	0.0278	1.99
		1/8 x 1/2	20	0.227	18.1	96.9	99	0.0156	2.08
			40	1.02	74.5	87.3	100, 102	0.0641	2.11
			100	3.08	206.	66.6	101	0.1773	2.29
0-10 μ	4.0	1/16 x 1/8	20	0.292	2.91	98.5	21, 22	0.0040	3.75
			100	3.33	33.2	90.8	9-20, 52-69	0.0463	2.08
		1/8 x 1/2	20	0.328	24.5	92.1	25, 26	0.0342	2.39
			40	1.15	84.0	76.7	27, 28	0.1172	2.26
			100	3.35	243.	47.7	29, 30	0.339	2.18

* Details of runs given in Appendix C.

† Details of fly ash properties given in Appendix B.

‡ Calculated from measured feeder disk speed and feeder disk dust rate calibration data.
 $Q_{eav} = 2cD_{32}L_w / (1/T)(3L_w/p)$, using $p = 2.46 g/cm^3$, $L = 30 ft$.

Table E-2

COMPARISON OF MEASURED AND CALCULATED AVERAGE EFFICIENCY FACTORS

Average Efficiency Factor				Particle Size Distribution Parameters	
Fly Ash Fraction	Measured* $Q_{e\text{ av}}$ (Transmissometer)	Calculated [†] $\bar{Q}_e$		Geometric Standard Deviation σ_g	Sauter Diameter D_{32} Microns
		$\lambda = 0.7\mu$	$\lambda = 1.06\mu$		
0-2.5 μ	2.73	2.76	3.22	1.5	1.7
2.5-5 μ	2.46	2.37	2.57	1.5	3.1
5-10 μ	2.12	2.24	2.31	1.5	6.5
0-10 μ	2.53 (2.23) [‡]	2.54	2.63	2.2	4.0

* Average value from last column of Table E-1.

† Calculated from $\bar{Q}_e = \frac{\sum Q_e D_p^2 \Delta n_p}{\sum D_p^2 \Delta n_p}$ for an assumed log-probability

distribution with parameters taken from the last two columns of Table B-4, as summarized in the last two columns above.

‡ Omitting one value in Table E-1 that was abnormally high and of questionable precision.

Appendix F

LIDAR INSTRUMENTATION

The SRI Mark V lidar system (Figure F-1) was used to collect backscatter data at a wavelength of 1.06μ (neodymium laser), and the SRI/EPA Mark VIII lidar was used to collect backscatter data at a wavelength of 0.69μ (ruby laser). Table F-1 gives the lidar characteristics and Figure F-2 is a diagram of the transmitter/receiver optics and of the data recording method used with the Mark V lidar. The transmitter and receiver optics are coaxial so that complete beam convergence occurs at a short range from the lidar (approximately 50 m). A small portion of the beam energy is reflected by means of a glass plate beam splitter onto a diffusing surface that is viewed by a light pipe with a wide acceptance angle. The output from the light pipe is reflected into one of the photomultiplier tubes, and the resulting pulse amplitude is used to normalize the pulse amplitude returns from both the chamber aerosol and the passive reflector. Since the peak return from the aerosol is proportional to transmitted energy and the return from the reflector is proportional to transmitted peak power, it is assumed that the ratio between these quantities remains constant from pulse to pulse, i.e., the transmitter pulse shape does not vary. Because of the high bandpass of the lidar signals, a photographic technique is employed to record the data records. Linear signal processing and displaying was used because of normal uncertainties of the transfer characteristics of the video logarithmic amplifier. However, because the lidar return signals may vary over several orders of magnitude, a multistage display scheme was used. The output from one detector is input to three separate oscilloscope displays, each set

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at a different voltage gain. The output from the other detector was logarithmically amplified and displayed on an oscilloscope to provide a single trace monitor of the energy return along the beam path. Data recorded with the Mark VIII lidar, which has only one detector, was recorded using a single higher bandpass Tektronix 556, dual-beam oscilloscope (30 MHz) with two linear displays.

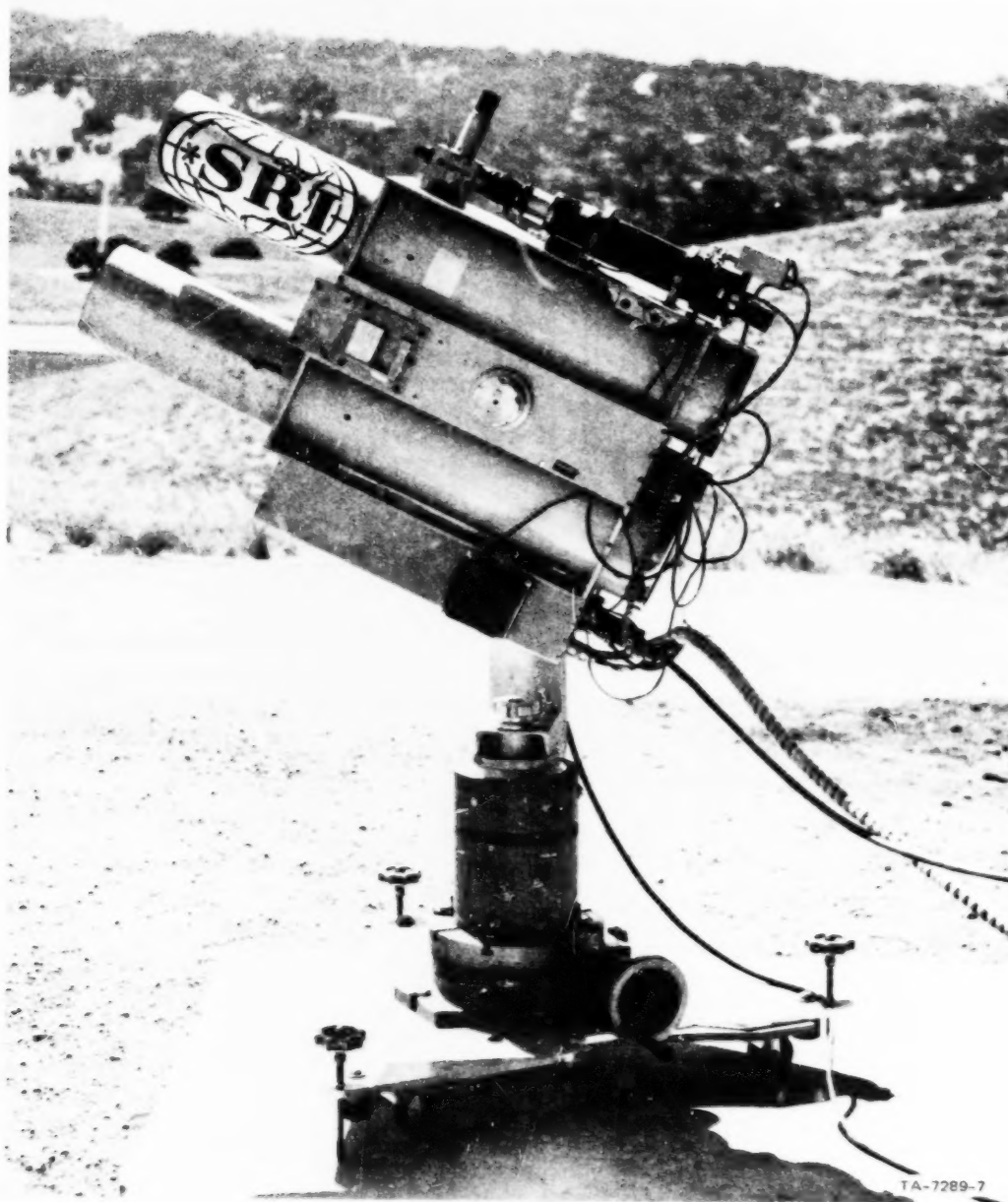
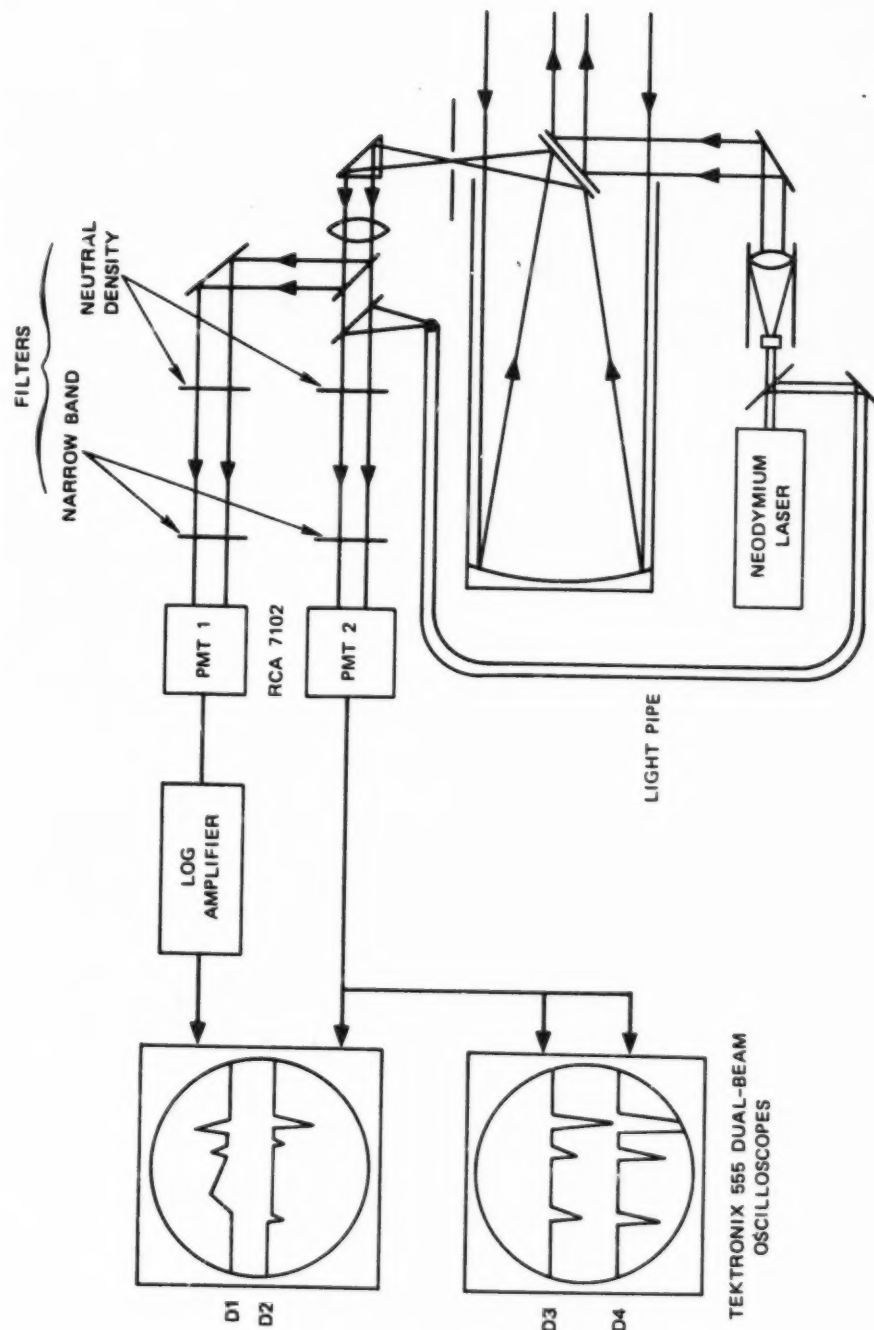


FIGURE F-1 SRI MARK V LIDAR



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FIGURE F-2 DIAGRAM OF MARK V LIDAR SYSTEM AND DATA RECORDING FOR BACKSCATTER EXPERIMENTS

Table F-1

CHARACTERISTICS OF SRI/EPA MARK VIII AND SRI MARK V LIDAR

SRI/EPA Mark VIII Lidar	Characteristics
Transmitter	
Laser Rod	Ruby
Wavelength ($\text{\AA}$)	6943.0
Beamwidth (mrad)	Measured as 2 mrad and reduced to 1 mrad during this study
Optics	2-inch refractor coaxial with receiver telescope
Pulse Energy (joules)	0.9
Pulse Length (nsec)	Measured as 50 ns during this study
Q-Switch	Pockels cell
Cavity Cooling	Refrigerated water
Receiver	
Optics	Newtonian reflector (6-in.)
Field of View (mrad)	2 and 3 mrad used during this study
Predetection Filter Passband Width ($\text{\AA}$)	10
Neutral Density Filter	16 dB
Detector	RCA-7265 photomultiplier (S-20 cathode)
Post Detection Filter Bandwidth	30 MHz
SRI Mark V Lidar	
Transmitter	
Laser Rod	Neodymium glass
Wavelength ($\text{\AA}$)	10,600
Spectral Line Width ($\text{\AA}$)	90
Beamwidth (mrad)	0.4
Optics	2-inch refractor, coaxial with receiver telescope
Pulse Energy (joules)	1.0
Pulse Length (nsec)	Measured as 23 nsec during this study
Q-Switched	Rotating prism
Receiver	
Optics	Newtonian reflector (6 in.)
Field of View (mrad)	1.0
Predetection Filter Passband Width ($\text{\AA}$)	100
Neutral Density Filter	30 dB
Detector	RCA 7102 photomultiplier (S-1 cathode)
Post Detection Filter Bandwidth	30 MHz

Appendix G

LIDAR SIGNATURE ANALYSIS

Figure G-1 is an example of the lidar signatures recorded for various fly ash concentrations (Mark VIII lidar, 0-2.5 μm diameter fly ash). The amplitude of the pulse at zero range is a measure of the peak power emitted by the laser. As the aerosol concentration is increased, the return from the passive reflector decreases because of the round-trip attenuation of the laser pulse by the aerosol. The amplitude of the aerosol return signal (normalized by the transmitted energy) increases with increases of aerosol concentration. The primary data records consist of three pulses P_t , P_a , and P_r , that are proportional to the peak transmitted power (P'_t), the peak aerosol return (P'_a), and the peak passive reflector return (P'_r). The relationship among these quantities and the derivation of their information content are best approached by use of lidar equations for solid and volume targets that may be expressed in the form:

$$\text{Solid target: } P'_r = K P'_t R^{-2} \frac{r}{\pi} T_c^2 T_a^2 \quad \text{G-1}$$

$$\text{Volume target: } P'_a = K P'_t R^{-2} \beta \frac{\tau}{2} T_c^2 \quad \text{G-2}$$

where

K = lidar constant

P'_t = peak power transmitted

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G-3

- R = range to the target
 r = target reflectivity
 β = volume backscatter coefficient
 τ = pulse length
 T_c = transmission along the path of clear air
 T_a = transmission along the path of the test (chamber) aerosol.

The above expressions assume single scattering, no geometrical effects over the beam path (coaxial lidar), negligible attenuation over one laser pulse length, uniformly distributed scatters within the pulse, and a Lambert (cosine) reflector. For a given lidar, the quantities K , R_r , R_a , r , and τ are assumed to remain constant. The constant τ implies that the ratio of transmitted energy to peak power (or pulse shape) remains constant from pulse to pulse.

Relative backscatter of the chamber aerosol is defined as a quantity normalized by transmitted energy, not corrected, however, for variations of the clear air transmission, i.e.,

$$\beta_R \equiv \text{relative backscatter} \equiv \frac{P_a}{P_t} \quad . \quad G-3$$

This quantity is dependent on the lidar optical and electrical efficiencies and hence its numerical values would vary from lidar to lidar. An absolute value of backscatter, the volume backscatter coefficient, requires calibration of the lidar, which may be accomplished by use of a solid target (passive reflector) of known reflectivity. The ratio of returns from a solid target to a volume target leads to the expression:

$$\beta = \frac{P_a}{P_r} \frac{R_a^2}{R_r^2} \frac{r}{\pi} T_a^2 \quad . \quad G-4$$

The backscatter experiments required a black passive reflector so that received signals were not sufficiently large to fall in a nonlinear operating region of the detector (detector saturation). The target reflectivity (0.07) was determined from the ratio of reflected target returns from the black target and a standard white target (0.98 reflectivity) with a neutral density filter placed in the receiver to prevent detector saturation. Pulse lengths were measured before the backscatter experiments using a photodiode and a high bandpass oscilloscope (Tektronix 556). Pulse shapes were not monitored during the experiments.

Transmission of the laser energy pulse through the aerosol chamber T_a , may be derived from the transmissometer data or inferred from the lidar data. Using the data recorded from a lidar observation made with a clear air aerosol chamber c , the transmission for a test aerosol may be evaluated from the expression:

$$T_a^2 = \frac{P_{tc}}{P_{rc}} \cdot \frac{P_r}{P_t} \quad , \quad G-5$$

where the transmission through a "clear" chamber, T_{ac} , was assumed to be unity. Using the lidar derived value of T_a , the expression for β becomes:

$$\beta = \frac{P_a}{P_t} \frac{P_{tc}}{P_{rc}} \frac{R_a^2}{R_r^2} \frac{r}{\pi} \frac{2}{\pi} \quad G-6$$

$$\beta = \text{const} \cdot \frac{P_a}{P_t} \quad G-7$$

G-5

and β is independent of the target return for lidar firings with a test aerosol within the chamber. This is important for the backscatter experiments since high aerosol concentrations may result in weak target returns that cannot accurately be read from the primary data records. A relative backscatter quantity corrected for variations of the clear air transmission over the 500-ft path, T_c , can be derived (Eq. G-6) from the expression

$$\beta'_R = \frac{P_a}{P_t} \frac{P_{tc}}{P_{rc}} = \beta_R \frac{P_{tc}}{P_{rc}} \quad G-8$$

The value of T_a in Eq. (G-4) can be replaced by the transmission determined with the white light transmissometer. This transmission measurement is probably a better indicator of the true laser energy transmission (because of less experimental error); however, Eq. (G-4) then requires a reading of target return energy, P_r , at times of high aerosol concentration. Hence, enhanced experimental errors could be expected at large aerosol concentrations.

The quantities P_t , P_a , and P_r were read from the Polaroid prints as voltages above the receiver noise level that, because of the black target, was electronic noise limited rather than atmospheric background limited. The data were placed on computer input cards and subjected to the above analysis and then plotted in various ways by a computer microfilm plotting system. The data are tabulated in Appendix H and shown as data plots in Section III C of the main text.

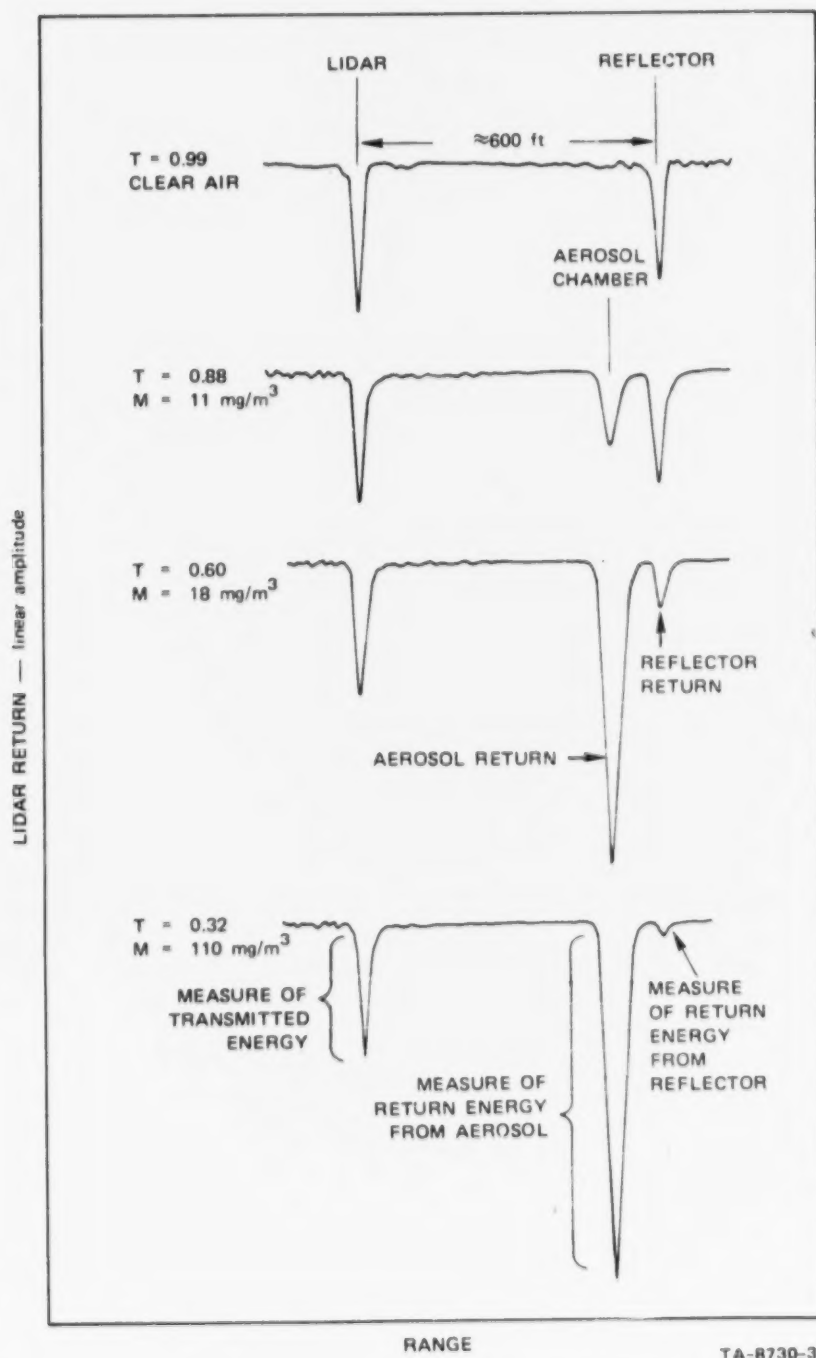


FIGURE G-1 EXAMPLES OF LIDAR SIGNATURES (REPRODUCED FROM POLAROID PRINTS) FOR VARIOUS MASS CONCENTRATIONS OF THE 0- TO 2.5- μ DIAMETER FLY ASH FRACTION (0.6943 μ WAVELENGTH LIDAR)

Appendix H

LIDAR DATA SUMMARY

The lidar data collected and analyzed under the present study are summarized in Table H-1 in digital form. Absolute power levels were not measured because the photomultiplier gain and/or receiver attenuation for various experimental phases had to be varied. System studies applied to other lidar techniques are best approached using the absolute scattering and extinction coefficients presented in Section III-C of the main text. The relative returns (voltages) shown in Table H-1 may be applied to any lidar by calibrating the lidar in terms of received signal from a black diffuse passive reflector.

Table H-1

LIDAR DATA SUMMARY

Run No.	Lidar (wavelength)	Fly Ash Fraction	Feeder Groove Size
1	Mk V (1.06 μ)	0-10	1/16 x 1/8
2	Mk V (1.06 μ)	0-10	1/8 x 1/2
3	Mk V (1.06 μ)	0-2.5	1/8 x 1/2
4	Mk V (1.06 μ)	2.5-5	1/8 x 1/2
6	Mk VIII (0.69 μ)	2.5-5	1/8 x 1/2
7	Mk VIII (0.69 μ)	0-2.5	1/8 x 1/2
8	Mk VIII (0.69 μ)	0-2.5	1/8 x 1/2
9	Mk VIII (0.69 μ)	0-10	1/8 x 1/2
10	Mk VIII (0.69 μ)	0-10	1/8 x 1/2
11	Mk VIII (0.69 μ)	Screen Experiment	
12	Mk VIII (0.69 μ)	5-10	1/8 x 1/2
13	Mk VIII (0.69 μ)	0-2.5	1/16 x 1/8
14	Mk VIII (0.69 μ)	0-10	1/16 x 1/8

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Table H-2 contains printouts of computer runs. A glossary of terms used in the column headings precedes the table.

Glossary for Terms in Table H-2

- D = particle feeder speed control setting
- P_t = relative transmitted peak power (mV)
- P_a = relative aerosol peak power return (mV)
- P_r = relative passive reflector (black) return (mV)
- P_r^{*} = relative passive reflector (white) return (mV)
- P_s = relative screen return (mV)
- T = transmission (white light)
- σ = volume extinction coefficient (km⁻¹)
- M = aerosol mass concentration (mg/m³)

Table H-2

DIGITAL DATA FROM INDIVIDUAL RUNS

LYDAR FIELD DATA, RUN NO. 1								
D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	-	M
0	1500	-ñ	300	0.000	.253	.997	.33	.11
0	1550	-ñ	350	0.000	.226	.997	.33	.11
0	1450	-ñ	300	0.000	.207	.997	.33	.11
0	1300	-ñ	320	0.000	.246	.997	.33	.11
0	1030	-ñ	250	0.000	.243	.997	.33	.11
0	1300	-ñ	300	0.000	.231	.997	.33	.11
0	1650	-ñ	420	0.000	.255	.997	.33	.11
0	1450	-ñ	300	0.000	.207	.997	.33	.11
AVG	1404	ñ	327	0.000	.233	.997	.33	.11
20	1550	1ñ	320	.012	.206	.992	.88	.29
20	1400	1ñ	300	.013	.214	.990	1.10	.37
20	1500	2ñ	350	.015	.233	.988	1.32	.44
20	1580	2ñ	310	.014	.196	.986	1.54	.52
20	1650	24	400	.015	.242	.986	1.54	.52
AVG	1536	21	336	.014	.219	.988	1.27	.43
40	1520	7ñ	300	.046	.197	.967	3.66	1.23
40	1700	9ñ	400	.053	.215	.966	3.77	1.27
40	1650	8ñ	360	.048	.218	.967	3.66	1.23
40	1810	8ñ	360	.044	.199	.965	3.89	1.31
40	1450	12ñ	340	.083	.234	.948	5.82	1.96
40	1650	13ñ	390	.082	.236	.945	6.17	2.07
40	1350	10ñ	295	.076	.219	.945	6.17	2.07
40	1380	10ñ	300	.076	.217	.947	5.94	2.00
40	1550	17ñ	340	.110	.219	.929	8.03	2.70
40	1520	17ñ	360	.112	.237	.933	7.56	2.54
40	1280	14ñ	260	.109	.203	.932	7.68	2.58
40	1290	16ñ	280	.124	.217	.935	7.33	2.46
AVG	1512	11ñ	332	.080	.219	.948	5.81	1.95
100	1530	22ñ	300	.144	.196	.909	10.40	3.50
100	1480	23ñ	300	.155	.203	.890	11.61	3.90
100	1550	24ñ	300	.155	.194	.901	11.37	3.82
100	1710	27ñ	350	.158	.205	.899	11.61	3.90
AVG	1567	24ñ	313	.153	.199	.902	11.25	3.78

LYDAR FIELD DATA, RUN NO. 2								
D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	-	M
0	800	-ñ	540	0.000	.675	.995	.55	.18
0	880	-ñ	750	0.000	.852	.995	.55	.18
0	1200	-ñ	900	0.000	.750	.995	.55	.18
0	800	-ñ	660	0.000	.825	.995	.55	.18
0	1250	-ñ	1100	0.000	.880	.995	.55	.18
0	1150	-ñ	900	0.000	.783	.995	.55	.18
0	1250	-ñ	1100	0.000	.880	.995	.55	.18
AVG	1047	ñ	850	0.000	.806	.995	.55	.18
20	1050	25ñ	700	.238	.667	.928	8.15	2.74
20	1400	35ñ	1140	.250	.814	.922	8.86	2.98
20	800	18ñ	650	.225	.813	.923	8.74	2.94
20	1150	30ñ	890	.261	.774	.923	8.74	2.94
20	1280	38ñ	1000	.297	.781	.924	8.62	2.90
20	1380	36ñ	1200	.261	.870	.928	8.15	2.74
20	1320	34ñ	1120	.258	.848	.920	9.09	3.06
20	500	10ñ	340	.200	.680	.924	8.62	2.90
20	900	24ñ	660	.267	.733	.912	10.05	3.38
20	1000	24ñ	800	.240	.800	.916	9.57	3.21
AVG	1078	27ñ	850	.250	.778	.922	8.86	2.98

Table H-2 Continued

LIDAR FIELD DATA, RUN NO. 2 (CONTINUED)

D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	S	M
0	1200	-2	950	0.000	.792	-0.000	-0.00	-0.00
0	1400	-2	1000	0.000	.714	-0.000	-0.00	-0.00
0	2000	-2	1620	0.000	.810	-0.000	-0.00	-0.00
0	1200	-2	810	0.000	.675	-0.000	-0.00	-0.00
AVG	1450	0	1095	0.000	.748	0.000	0.00	0.00
40	800	500	310	.625	.387	.758	30.22	10.15
40	850	510	400	.600	.471	.745	29.21	9.82
40	1450	850	610	.586	.421	.767	28.93	9.72
40	1250	750	610	.600	.488	.760	29.93	10.06
40	1300	820	600	.631	.462	.751	31.23	10.49
AVG	1130	684	506	.608	.446	.760	29.90	10.05
100	1000	1100	200	1.100	.200	.494	76.91	25.84
100	1000	1000	150	1.000	.150	.488	78.24	26.29
100	880	880	140	1.000	.159	.491	77.57	26.09
100	700	800	120	1.143	.171	.489	78.01	26.21
100	850	850	100	1.000	.118	.491	77.57	26.06
AVG	886	944	142	1.067	.160	.491	77.66	26.09
0	300	-2	150	0.000	.500	-0.000	-0.00	-0.00
0	1100	-2	650	0.000	.591	-0.000	-0.00	-0.00
AVG	700	0	400	0.000	.545	0.000	0.00	0.00
100	600	600	100	1.000	.167	.496	76.46	25.69
100	1350	1150	160	.852	.119	.497	76.24	25.62
100	1610	1550	260	.963	.161	.498	76.03	25.54
100	1350	1300	200	.963	.148	.496	76.46	25.69
100	1640	1500	300	.915	.183	.493	77.13	25.91
AVG	1310	1220	204	.938	.156	.496	76.47	25.69

LIDAR FIELD DATA, RUN NO. 3

D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	S	M
0	1620	-2	1480	0.000	.914	.998	.22	.21
0	1400	-2	1300	0.000	.929	.998	.22	.21
0	1450	-2	1300	0.000	.897	.998	.22	.21
AVG	1490	0	1360	0.000	.913	.998	.22	.21
20	1600	600	1200	.375	.750	.902	11.25	10.61
20	1250	400	910	.320	.728	.913	9.93	9.36
20	1300	530	860	.408	.662	.907	10.64	10.04
20	1500	460	1100	.307	.733	.900	11.49	10.83
20	1580	500	1150	.316	.728	.881	13.82	13.03
20	1380	500	910	.362	.659	.896	11.98	11.29
20	1240	390	800	.319	.645	.892	12.46	11.75
20	1550	400	1250	.258	.806	.867	15.54	14.68
20	1400	400	900	.286	.643	.881	13.82	13.03
20	1480	400	1100	.270	.743	.892	12.46	11.75
20	1900	530	1400	.279	.778	.861	16.32	15.39
AVG	1462	460	1053	.320	.716	.890	12.70	11.98
0	1200	-2	1050	0.000	.875	.998	.22	.21
0	1150	-2	920	0.000	.800	.998	.22	.21
0	1060	-2	930	0.000	.877	.998	.22	.21
0	900	-2	740	0.000	.822	.998	.22	.21
AVG	1077	0	910	0.000	.844	.998	.22	.21
100	1500	1600	200	1.067	.133	.430	92.04	86.79
100	1490	1630	250	1.094	.168	.420	94.60	89.21
100	1800	1600	300	.889	.167	.422	94.08	88.72
AVG	1597	1610	250	1.017	.156	.424	93.57	88.24

Table H-2 Continued

LIDAR FIELD DATA, RUN NO. 3 (CONTINUED)								
D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T		M
40	750	500	250	.667	.333	.630	50.39	47.51
40	1100	800	460	.727	.418	.680	42.06	39.66
40	1350	1100	600	.815	.444	.630	50.39	47.51
40	1300	1100	500	.846	.385	.631	50.21	47.35
40	1600	1250	600	.781	.375	.628	50.73	47.84
40	1650	1300	700	.836	.424	.537	67.80	63.94
40	1600	1200	750	.750	.469	.628	50.73	47.84
40	1900	1500	850	.789	.447	.625	51.25	48.33
40	1300	850	700	.654	.538	.625	51.25	48.33
40	1200	900	450	.750	.375	.731	34.17	32.22
AVG	1375	1054	586	.762	.421	.634	49.90	47.05
0	400	-A	300	0.000	.750	.998	.22	.21
0	600	-A	450	0.000	.750	.998	.22	.21
0	450	-A	350	0.000	.778	.998	.22	.21
0	850	-A	700	0.000	.824	.998	.22	.21
0	1000	-A	900	0.000	.900	.998	.22	.21
AVG	660	-A	540	0.000	.800	.998	.22	.21
100	650	900	50	1.385	.077	.259	147.32	138.92
100	1150	1450	100	1.261	.087	.301	130.93	123.47
100	1300	1700	80	1.308	.062	.266	144.41	136.18
100	1100	1400	90	1.273	.082	.326	122.23	115.26
100	1100	1400	80	1.273	.073	.304	129.45	122.45
100	1160	1450	80	1.250	.069	.293	133.87	126.24
100	1000	1300	80	1.300	.080	.296	132.76	125.19
AVG	1066	1371	80	1.293	.076	.292	134.48	126.82

LIDAR FIELD DATA, RUN NO. 4								
D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T		M
0	1900	-A	1400	0.000	.737	.995	.55	.25
0	1600	-A	1100	0.000	.688	.995	.55	.25
0	1600	-A	1100	0.000	.688	.995	.55	.25
0	1900	-A	1400	0.000	.737	.995	.55	.25
AVG	1765	-A	1272	0.000	.718	.995	.55	.25
40	1150	750	300	.647	.259	.735	33.58	15.11
40	1550	1050	500	.677	.323	.748	31.66	14.25
40	1200	800	400	.667	.333	.747	31.81	14.31
40	1300	900	400	.692	.308	.754	30.79	13.86
40	1650	1200	600	.727	.364	.752	31.08	13.99
40	1300	900	430	.692	.331	.732	34.02	15.31
40	1750	1100	600	.629	.343	.752	31.08	13.99
40	1600	1000	500	.625	.313	.817	22.04	9.92
40	1550	1100	400	.710	.258	.740	32.84	14.78
40	900	600	250	.667	.278	.740	32.84	14.78
40	1100	650	300	.591	.271	.740	32.84	14.78
40	1400	900	400	.643	.286	.740	32.84	14.78
40	1300	1000	450	.769	.346	.740	32.84	14.78
40	1600	1100	600	.702	.357	.740	32.84	14.78
AVG	1389	938	438	.674	.312	.748	31.65	14.24
0	800	-A	400	0.000	.500	.995	.55	.25
0	1400	-A	750	0.000	.536	.995	.55	.25
0	1600	-A	1000	0.000	.625	.995	.55	.25
AVG	1267	-A	717	0.000	.554	.995	.55	.25

Table H-2 (Continued)

LIDAR FIELD DATA, RUN NO. 4 (CONTINUED)

D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	σ	M
40	1400	75 $\bar{a}$	350	.536	.250	.738	33.13	14.91
40	1400	100 $\bar{a}$	500	.714	.357	.731	34.17	15.38
40	1550	110 $\bar{a}$	450	.710	.290	.724	35.22	15.85
40	1450	98 $\bar{a}$	450	.676	.310	.742	32.54	14.64
40	1350	100 $\bar{a}$	450	.741	.333	.751	31.23	14.05
40	1700	110 $\bar{a}$	570	.647	.335	.715	36.58	16.46
AVG	1475	98 $\bar{a}$	462	.671	.313	.733	33.81	15.22
n	1300	- $\bar{a}$	700	0.000	.538	.995	.55	.25
n	1500	- $\bar{a}$	900	0.000	.600	.995	.55	.25
AVG	1400	$\bar{a}$	800	0.000	.569	.995	.55	.25
40	1400	100 $\bar{a}$	400	.714	.286	.740	32.84	14.78
40	1700	125 $\bar{a}$	500	.735	.294	.728	34.62	15.58
40	1600	110 $\bar{a}$	560	.688	.350	.728	34.62	15.58
40	1500	110 $\bar{a}$	500	.733	.333	.726	34.92	15.71
AVG	1550	111 $\bar{a}$	490	.718	.316	.730	34.25	15.41
0	1300	- $\bar{a}$	700	0.000	.538	.995	.55	.25
0	1600	- $\bar{a}$	600	0.000	.600	.995	.55	.25
AVG	1150	$\bar{a}$	650	0.000	.569	.995	.55	.25
20	1380	40 $\bar{a}$	700	.290	.507	.890	12.71	5.72
20	1200	36 $\bar{a}$	610	.300	.508	.927	8.27	3.72
20	1610	50 $\bar{a}$	810	.311	.503	.922	8.86	3.99
20	1600	50 $\bar{a}$	900	.313	.563	.924	8.62	3.88
20	1060	25 $\bar{a}$	540	.236	.509	.928	8.15	3.67
20	920	20 $\bar{a}$	500	.217	.541	.918	9.33	4.20
AVG	1295	36 $\bar{a}$	677	.278	.522	.918	9.32	4.19
0	1210	- $\bar{a}$	690	0.000	.570	.995	.55	.25
0	1150	- $\bar{a}$	700	0.000	.609	.995	.55	.25
0	1300	- $\bar{a}$	900	0.000	.692	.995	.55	.25
AVG	1220	$\bar{a}$	763	0.000	.624	.995	.55	.25
20	1000	29 $\bar{a}$	480	.290	.480	.918	9.33	4.20
20	1430	30 $\bar{a}$	800	.210	.559	.927	8.27	3.72
20	1100	35 $\bar{a}$	600	.318	.545	.910	10.28	4.63
20	1300	33 $\bar{a}$	650	.254	.500	.911	10.16	4.57
AVG	1217	31 $\bar{a}$	632	.268	.521	.916	9.51	4.28
0	1250	- $\bar{a}$	700	0.000	.560	.995	.55	.25
0	950	- $\bar{a}$	600	0.000	.632	.995	.55	.25
0	1200	- $\bar{a}$	800	0.000	.667	.995	.55	.25
AVG	1133	$\bar{a}$	700	0.000	.619	.995	.55	.25
100	1150	142 $\bar{a}$	100	1.235	.087	.424	93.57	42.11
100	1400	175 $\bar{a}$	150	1.250	.107	.418	95.12	42.81
100	1150	160 $\bar{a}$	120	1.391	.104	.428	92.54	41.64
100	1080	146 $\bar{a}$	120	1.352	.111	.406	98.30	44.23
100	1100	160 $\bar{a}$	130	1.455	.118	.418	95.12	42.81
100	1200	168 $\bar{a}$	150	1.400	.125	.417	95.38	42.92
100	1410	172 $\bar{a}$	150	1.220	.106	.413	96.43	43.40
100	1550	180 $\bar{a}$	160	1.161	.103	.415	95.91	43.16
100	1500	210 $\bar{a}$	200	1.400	.133	.417	95.38	42.92
AVG	1282	168 $\bar{a}$	142	1.318	.111	.417	95.31	42.89
0	1080	- $\bar{a}$	680	0.000	.630	.995	.55	.25
0	1160	- $\bar{a}$	710	0.000	.612	.995	.55	.25
n	1100	- $\bar{a}$	760	0.000	.691	.995	.55	.25
AVG	1113	$\bar{a}$	717	0.000	.644	.995	.55	.25

Table H-2 Continued

LYNAR FIELD DATA, RUN NO. 4								
D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	Q	M
0	315	-2	382	0.000	1.213	.995	.55	.25
0	368	-2	407	0.000	1.126	.995	.55	.25
0	360	-2	330	0.000	.917	.994	.66	.30
0	420	-2	502	0.000	1.195	.994	.66	.30
AVG	346	-2	405	0.000	1.108	.994	.60	.27
20	352	152	255	.432	.724	.925	8.50	3.83
20	375	288	352	.768	.939	.921	8.97	4.04
20	372	232	330	.624	.887	.923	8.74	3.93
20	427	232	360	.543	.843	.916	9.57	4.31
20	375	182	322	.490	.859	.921	8.97	4.04
20	420	282	372	.671	.886	.915	9.69	4.36
20	375	224	390	.600	1.040	.924	8.62	3.88
20	450	218	465	.484	1.033	.919	9.21	4.15
AVG	393	224	356	.575	.901	.920	9.03	4.07
0	315	-2	372	0.000	1.181	.993	.77	.34
0	344	-2	360	0.000	1.047	.991	.99	.44
0	382	-2	360	0.000	.942	.995	.55	.25
AVG	347	-2	364	0.000	1.057	.993	.77	.34
40	315	597	234	1.895	.743	.764	29.36	13.21
40	372	638	282	1.694	.758	.767	28.93	13.02
40	339	542	225	1.593	.664	.763	29.50	13.27
40	397	566	225	1.426	.567	.771	28.36	12.76
40	420	617	279	1.469	.664	.779	27.23	12.26
40	420	696	315	1.657	.750	.782	26.82	12.07
40	427	607	330	1.422	.773	.796	24.88	11.20
40	398	615	288	1.545	.724	.770	28.50	12.83
40	360	494	210	1.375	.583	.776	27.66	12.45
40	337	551	255	1.635	.757	.780	27.10	12.19
AVG	378	591	264	1.571	.698	.775	27.43	12.52
0	240	-2	307	0.000	1.279	.992	.99	.44
0	307	-2	330	0.000	1.075	.991	.99	.44
0	360	-2	375	0.000	1.042	.992	.88	.39
0	375	-2	450	0.000	1.200	.991	.99	.44
AVG	320	-2	365	0.000	1.149	.991	.93	.42
100	342	772	140	2.257	.409	.474	81.41	36.64
100	300	727	105	2.423	.350	.478	80.50	36.22
100	270	756	80	2.800	.296	.498	76.03	34.21
100	285	652	75	2.288	.263	.534	65.41	30.79
100	360	782	149	2.167	.469	.509	73.64	33.14
100	360	968	142	2.609	.394	.549	65.39	29.47
AVG	319	778	118	2.437	.364	.507	74.23	33.40

Table H-2 Continued

LYDAR FIELD DATA, RUN NO. 7								
D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	n	M
0	150	125	130	0.000	.867	.993	.77	.72
0	195	125	215	0.000	1.103	.993	.77	.72
0	175	125	160	0.000	.914	.993	.77	.72
0	145	125	160	0.000	.970	.993	.77	.72
AVG	171	125	166	0.000	.963	.993	.77	.72
20	140	125	95	.893	.679	.865	15.82	14.91
20	130	79	88	.554	.677	.915	7.33	6.91
20	150	94	125	.633	.833	.924	8.62	8.13
20	150	145	140	.967	.933	.888	12.45	12.22
20	185	154	135	.838	.730	.864	15.94	15.03
20	145	174	145	.919	.784	.871	15.06	14.20
20	100	92	75	.950	.750	.865	15.82	14.91
20	135	114	105	.845	.778	.877	14.31	13.50
AVG	147	121	113	.821	.770	.886	13.23	12.48
0	135	125	135	0.000	1.000	.991	.99	.93
0	140	125	55	0.000	.688	.991	.99	.93
0	140	125	145	0.000	1.036	.991	.99	.93
0	145	125	105	0.000	.724	.990	1.10	1.03
AVG	125	125	110	0.000	.862	.991	1.01	.96
40	160	344	65	2.125	.406	.628	50.73	47.84
40	164	388	65	2.366	.396	.634	49.70	46.86
40	155	309	55	1.994	.355	.625	51.25	48.33
40	135	300	42	2.222	.311	.608	54.26	51.17
40	165	405	65	2.455	.394	.601	55.52	52.36
40	140	400	58	2.500	.362	.623	51.40	48.66
40	115	264	45	2.313	.391	.631	50.21	47.35
40	138	312	65	2.261	.471	.641	48.50	45.73
AVG	149	344	58	2.279	.386	.624	51.47	48.54
0	95	125	95	0.000	1.000	.999	.11	.10
0	125	125	115	0.000	.920	.991	.99	.93
0	130	125	140	0.000	1.077	.995	.55	.52
AVG	117	125	117	0.000	.999	.995	.55	.52
100	93	278	25	2.989	.269	.432	91.53	86.31
100	105	294	35	2.900	.333	.565	62.26	58.71
100	124	255	60	1.992	.449	.728	37.66	35.51
100	124	366	39	2.952	.315	.547	65.79	62.04
100	128	357	41	2.789	.320	.514	72.58	68.44
100	125	377	35	3.014	.280	.515	72.37	68.74
100	142	314	28	3.088	.275	.514	72.58	68.44
100	125	354	40	2.848	.320	.513	72.79	68.64
100	115	369	35	3.209	.304	.482	79.59	75.15
100	140	374	40	2.671	.286	.528	69.65	65.68
100	128	374	40	2.891	.313	.561	63.74	59.64
AVG	119	337	38	2.840	.317	.534	69.77	65.14

Table H-2 Continued

LYDAR FIELD DATA, RUN NO. 4								
D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	C	M
20	73	55	75	.753	1.027	.911	10.16	9.59
20	114	68	93	.596	.816	.872	14.94	14.08
20	75	73	75	.973	1.000	.875	14.56	13.73
20	118	64	100	.559	.847	.883	13.57	12.80
20	113	95	105	.841	.929	.875	14.56	13.73
20	95	95	85	1.000	.895	.870	15.19	14.32
AVG	98	75	89	.787	.919	.881	13.83	13.04
40	95	195	60	2.053	.632	.630	50.39	47.51
40	120	325	44	2.708	.367	.604	54.98	51.85
40	134	384	62	2.866	.463	.612	53.55	50.49
40	129	372	55	2.884	.426	.592	57.17	53.91
40	120	300	50	2.500	.417	.606	54.62	51.51
AVG	120	315	54	2.602	.441	.609	54.14	51.05
100	95	375	8	3.947	.084	.231	159.80	150.69
100	100	375	13	3.750	.130	.357	112.32	105.92
100	95	487	8	5.126	.084	.270	142.78	134.45
100	124	495	13	3.992	.105	.320	124.24	117.17
100	148	465	8	4.306	.074	.276	140.39	132.39
100	125	522	15	4.176	.120	.310	127.72	120.44
100	130	540	10	4.154	.077	.257	148.17	139.72
AVG	111	464	11	4.207	.096	.289	136.49	128.71

LYDAR FIELD DATA, RUN NO. 9								
D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	C	M
0	95	-2	100	0.000	1.053	.999	.11	.04
0	125	-2	125	0.000	1.000	.999	.11	.04
0	125	-2	93	0.000	.744	.999	.11	.04
0	114	-2	78	0.000	.684	.997	.33	.11
0	128	-2	110	0.000	.859	.999	.11	.04
AVG	117	-2	101	0.000	.868	.999	.15	.05
20	108	85	95	.787	.787	.900	11.49	3.86
20	155	74	109	.503	.703	.913	9.93	3.34
20	132	100	110	.758	.833	.900	11.49	3.86
20	110	65	70	.591	.636	.907	10.64	3.58
20	158	82	145	.557	.918	.915	9.69	3.25
20	133	90	108	.677	.812	.894	12.22	4.11
20	160	74	120	.467	.750	.896	11.98	4.02
20	139	85	115	.612	.827	.892	12.46	4.19
AVG	137	84	108	.621	.783	.902	11.24	3.78
0	120	-2	145	0.000	1.208	.993	.77	.26
0	120	-2	100	0.000	.833	.993	.77	.26
0	115	-2	92	0.000	.800	.992	.88	.29
0	115	-2	110	0.000	.957	.993	.77	.26
AVG	117	-2	112	0.000	.950	.993	.79	.27
40	115	205	85	1.783	.739	.749	31.52	10.59
40	120	200	80	1.667	.667	.750	31.37	10.54
40	138	210	90	1.522	.652	.754	30.78	10.35
40	140	180	80	1.300	.571	.741	29.78	10.01
40	120	160	62	1.358	.517	.759	30.07	10.10
40	132	190	100	1.477	.758	.759	30.07	10.10
40	145	190	88	1.324	.607	.767	28.93	9.72
40	118	184	85	1.568	.720	.755	30.45	10.30
AVG	128	191	84	1.500	.654	.757	30.40	10.21

Table H-2 Continued

LIDAR FIELD DATA, RUN NO. 9 (CONTINUED)

D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	J	M
0	85	-2	105	0.000	1.235	.993	.77	.26
0	131	-2	140	0.000	1.069	.994	.66	.22
0	128	-2	122	0.000	.953	.994	.66	.22
AVG	115	-2	122	0.000	1.086	.994	.69	.23
100	120	362	31	3.000	.258	.494	76.91	25.84
100	135	405	45	3.000	.333	.497	76.74	25.62
100	149	338	35	3.101	.321	.490	77.79	26.14
100	125	345	30	2.760	.240	.491	77.57	26.06
100	125	362	35	2.880	.280	.487	78.46	26.36
100	115	345	35	3.000	.304	.491	77.57	26.06
100	130	375	39	2.885	.300	.495	76.68	25.77
100	119	318	29	2.672	.244	.489	78.01	26.21
AVG	122	358	35	2.912	.285	.492	77.41	26.01

LIDAR FIELD DATA, RUN NO. 10

D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	J	M
0	99	-2	99	0.000	1.000	.993	.77	.26
0	105	-2	120	0.000	1.143	.994	.66	.22
0	140	-2	145	0.000	1.036	.993	.77	.26
0	120	-2	132	0.000	1.100	.993	.77	.26
AVG	116	-2	124	0.000	1.070	.993	.74	.25
20	100	45	94	.450	.940	.922	8.86	2.98
20	125	55	110	.440	.880	.937	7.10	2.38
20	115	45	100	.391	.870	.931	7.80	2.62
20	115	55	98	.435	.852	.920	9.09	3.06
AVG	114	49	100	.429	.885	.927	8.21	2.76
40	98	145	70	1.429	.714	.774	27.94	9.39
40	118	125	70	1.059	.593	.798	24.61	8.27
40	115	145	70	1.217	.609	.781	26.96	9.06
40	135	168	102	1.222	.756	.788	25.98	8.73
AVG	116	142	78	1.232	.668	.785	26.37	8.86
100	98	302	42	3.061	.429	.542	66.79	22.44
100	124	318	38	2.565	.306	.543	66.59	22.37
100	128	314	46	2.453	.359	.542	66.79	22.44
100	105	311	30	2.942	.286	.504	74.72	25.11
100	130	308	35	2.369	.269	.514	72.58	24.39
AVG	117	312	38	2.682	.330	.529	69.49	23.35

LIDAR FIELD DATA, RUN NO. 11

D	P _t	P _s	P _r	P _s /P _t	P _r /P _t
0	139	-2	155	0.000	1.115
0	130	-2	145	0.000	1.115
0	148	-2	152	0.000	1.027
0	144	-2	165	0.000	1.146
0	138	-2	175	0.000	1.268
0	129	-2	130	0.000	1.014
0	145	-2	142	0.000	.979
0	135	-2	138	0.000	1.022
0	140	-2	150	0.000	1.071
0	132	-2	148	0.000	1.121
0	139	-2	140	0.000	1.007
AVG	138	-0	149	0.000	1.081

Table B-2 Continued

LIDAR FIELD DATA, RUN NO. 11 (CONTINUED)

D	P _t	P _s	P _r	P _s /P _t	P _r /P _t
0	140	-A	1040	0.000	13.143
0	135	-A	1040	0.000	13.630
0	129	-A	1920	0.000	15.360
0	124	-A	1030	0.000	16.758
0	140	-A	1780	0.000	12.714
0	125	-A	1040	0.000	14.720
0	131	-A	1750	0.000	13.359
0	105	-A	1650	0.000	15.714
0	125	-A	1920	0.000	16.360
AVG	127	-0	1819	0.000	14.306

D	P _t	P _s	P _r	P _s /P _t	P _r /P _t
0	130	434	80	3.338	.615
0	125	441	80	3.528	.704
0	125	441	85	3.528	.800
0	120	481	95	4.008	.792
0	130	424	85	3.277	.654
0	118	337	75	3.083	.694
0	119	365	80	3.067	.672
0	135	496	89	3.659	.859
0	120	479	88	3.992	.733
0	135	479	84	3.548	.622
0	134	498	88	3.662	.647
0	130	404	73	3.115	.562
AVG	126	440	81	3.184	.670

LIDAR FIELD DATA, RUN NO. 12

D	P _t	P _s	P _r	P _s /P _t	P _r /P _t	T	-	M
0	75	-A	84	0.000	1.120	.996	.44	.00
0	130	-A	140	0.000	1.159	.996	.44	.09
0	130	-A	150	0.000	1.215	.995	.55	.12
0	135	-A	168	0.000	1.244	.993	.77	.16
AVG	119	A	142	0.000	1.185	.995	.55	.12
20	130	34	120	.269	.923	.943	6.41	1.37
20	105	37	120	.296	1.143	.917	7.10	1.52
20	130	44	138	.308	1.062	.935	7.33	1.57
20	130	38	135	.292	1.038	.939	6.86	1.47
20	120	38	150	.317	1.250	.937	7.10	1.52
20	130	34	140	.269	1.077	.919	6.86	1.47
20	125	42	135	.336	1.080	.935	7.33	1.57
20	105	32	130	.305	1.238	.938	6.98	1.49
AVG	122	36	133	.298	1.101	.938	6.98	1.50
0	95	-A	132	0.000	1.389	.994	.66	.14
0	120	-A	130	0.000	1.083	.995	.55	.12
0	125	-A	150	0.000	1.200	.993	.77	.16
0	123	-A	142	0.000	1.154	.949	5.71	1.22
AVG	116	A	138	0.000	1.207	.983	1.92	.41

Table H-2 Continued

LIDAR FIELD DATA, RUN NO. 12 (CONTINUED)

D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	M
40	100	75	90	.694	.833	.858	16.70
40	120	85	92	.708	.767	.853	17.34
40	112	85	105	.759	.938	.854	17.21
40	110	75	85	.636	.773	.856	16.96
40	110	75	95	.682	.864	.858	16.70
40	118	85	92	.678	.780	.857	16.83
40	125	95	110	.736	.844	.853	17.14
AVG	115	85	97	.699	.843	.856	17.01
0	105	75	102	0.000	.971	.995	.55
0	122	75	118	0.000	.967	.993	.77
0	100	75	125	0.000	1.250	.995	.55
0	115	75	140	0.000	1.217	.995	.55
AVG	110	75	121	0.000	1.102	.994	.60
100	75	145	45	1.867	.600	.633	49.87
100	130	225	60	1.709	.462	.633	49.87
100	130	245	62	1.846	.477	.641	48.50
100	130	235	65	1.800	.500	.632	50.04
100	115	215	65	1.826	.565	.639	48.04
100	100	195	55	1.950	.550	.633	49.87
100	100	205	62	2.000	.620	.635	49.52
100	125	225	62	1.760	.496	.632	50.04
AVG	113	205	59	1.846	.534	.635	49.57

LIDAR FIELD DATA, RUN NO. 13

D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	M
0	105	75	110	0.000	1.124	.996	.44
0	92	75	108	0.000	1.174	.996	.44
0	90	75	100	0.000	1.111	.997	.33
0	80	75	98	0.000	1.225	.997	.33
AVG	92	75	106	0.000	1.158	.996	.36
20	100	15	105	.100	1.050	.982	1.98
20	80	11	78	.137	.975	.981	2.00
20	92	12	110	.130	1.196	.980	2.20
20	109	15	109	.130	1.000	.976	2.65
20	95	15	95	.105	1.000	.977	2.54
20	100	25	105	.220	1.050	.974	2.87
20	115	15	115	.104	1.000	.981	2.09
20	85	11	100	.129	1.176	.979	2.31
AVG	97	15	102	.133	1.056	.979	2.34
0	95	75	110	0.000	1.242	.934	7.45
0	102	75	100	0.000	.980	.986	1.54
AVG	98	75	109	0.000	1.111	.987	4.49
40	85	45	92	.565	1.082	.926	8.03
40	100	55	88	.580	.880	.916	9.57
40	118	55	118	.424	1.000	.926	8.38
40	109	31	106	.284	.972	.950	5.59
40	85	55	75	.612	.894	.904	11.01
40	98	35	95	.398	1.080	.934	7.45
40	111	25	91	.225	.820	.957	4.79
40	115	25	120	.209	1.122	.961	4.34
AVG	101	45	99	.412	.981	.935	7.40

Table H-2: Concluded

LIDAR FIELD DATA, RUN NO. 13 (CONTINUED)

D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	N
100	110	105	85	.955	.773	.851	17.59
100	104	94	88	.973	.846	.792	25.43
100	110	100	85	.909	.773	.842	18.75
100	110	105	98	.955	.891	.840	19.01
100	130	124	112	.965	.862	.795	25.02
100	105	89	82	.848	.781	.874	14.69
100	98	81	80	.827	.816	.869	15.31
100	104	124	100	1.231	.962	.842	18.75
AVG	109	104	91	.954	.839	.838	19.32
40	102	34	118	.333	1.157	.951	5.48
40	115	31	105	.270	.913	.951	5.48
40	110	29	108	.264	.982	.959	4.57
40	139	30	142	.281	1.022	.949	5.71
40	119	20	105	.264	.955	.953	5.75
40	122	30	149	.320	1.221	.954	5.14
40	110	24	105	.236	.955	.958	4.68
AVG	115	32	119	.281	1.029	.954	5.19

LIDAR FIELD DATA, RUN NO. 14

D	P _t	P _a	P _r	P _a /P _t	P _r /P _t	T	N
0	89	0	90	0.000	1.011	.993	.77
0	105	0	115	0.000	1.095	.992	.88
0	95	0	82	0.000	.863	.993	.77
0	90	0	100	0.000	1.111	.995	.55
AVG	95	0	97	0.000	1.020	.993	.74
20	85	10	106	.118	1.247	.978	2.43
20	85	8	85	.094	1.000	.986	1.54
20	100	0	105	.090	1.050	.981	2.19
20	118	10	135	.085	1.144	.980	2.20
20	109	0	130	.083	1.193	.983	1.87
AVG	99	0	112	.094	1.127	.982	2.03
40	94	25	95	.222	1.056	.962	4.22
40	72	21	90	.292	1.250	.959	4.57
40	99	21	88	.236	.989	.961	4.34
40	106	24	122	.245	1.151	.962	4.22
40	90	20	95	.222	1.056	.962	4.22
40	119	24	125	.202	1.050	.965	3.99
40	115	24	129	.243	1.122	.967	3.66
40	113	30	126	.265	1.115	.969	3.43
AVG	99	24	109	.241	1.099	.963	4.07
0	104	0	115	0.000	1.106	.997	.33
0	90	0	100	0.000	1.111	.997	.33
0	105	0	130	0.000	1.238	.997	.33
0	112	0	128	0.000	1.143	.997	.33
AVG	103	0	118	0.000	1.149	.997	.33
100	100	69	115	.620	1.150	.906	10.77
100	115	52	100	.452	.870	.906	10.77
100	89	52	95	.584	1.067	.906	10.77
100	110	61	110	.555	1.000	.908	10.52
100	94	48	78	.511	.830	.904	11.01
100	110	66	102	.591	.927	.906	10.77
100	109	62	109	.569	1.000	.908	10.52
100	104	60	110	.639	1.019	.907	10.64
AVG	104	59	102	.565	.963	.906	10.72
0	109	0	130	0.000	1.193	.981	2.09
0	104	0	110	0.000	1.058	.994	.56
0	129	0	159	0.000	1.233	.993	.77
0	110	0	132	0.000	1.200	.992	.88
AVG	113	0	133	0.000	1.171	.990	1.10